Acute effects of lightweight wearable resistance on coordination in general athletic skills among field-based athletes

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Abstract

Within field-based sport strength and conditioning, growing emphasis on the technical elements of general athletic skills, e.g. running, accelerating, and change of direction (COD), has required coaches to consider contemporary pedagogical approaches. These approaches are increasingly grounded in a complex systems perspective of movement. Constraints on complex systems limit degrees of freedom, which direct behavioural trajectories. Constraints therefore represent control parameters coaches can manipulate to encourage adoption of movements that may benefit performance, or induce variability, facilitating movement exploration and implicit skill development. Lightweight wearable resistance (WR) is a constraint worth considering in this framework. This thesis investigated the acute effects of WR on performance and coordination of overground running, early and late acceleration, and COD among field-based athletes. Biomechanical analyses describing nonlinear changes in movement, body segment interactions, and movement variability were implemented. Consideration was given to individual-level WR effects given pedagogical interventions aimed at altering technique are often individual-based.

Study one considered WR in overground running. Statistical parametric mapping of lower limb sagittal plane kinematics revealed that athletes exhibited decreased ankle plantarflexion following toe-off and increased knee flexion during weight acceptance with lower limb WR addition equivalent to 5% of body weight. A subset of participants exhibited increased repetition-to-repetition joint angle variability at one or more joints upon WR addition. Coaches must consider the varying responses between individuals and recognise that loading above a certain magnitude may limit movement options.

Study two investigated WR in early acceleration. Hierarchical agglomerative clustering showed that relatively heavy thigh WR affected whole body coordination to a greater extent than relatively heavy shank WR among five Australian Rules football athletes. Within thigh WR, posteriorly oriented WR led to altered pelvic position and greater hip extension, while anteriorly oriented WR led to accentuated shoulder movement. Coaches may use the findings as a starting point for WR application to direct coordination in acceleration, noting varying individual responses.

In late acceleration, which was the focus of study three, the effects of anterior and posterior thigh WR on kinetic and kinematic parameters were investigated. Peak propulsive force and propulsive impulse appeared accentuated by anterior thigh WR, while hip joint absolute rotational work during hip extension increased with posterior thigh WR. Neither WR configuration affected acceleration technique according to a “front-side mechanics” technical model of sprinting. The findings indicate parameters that may be emphasised by WR during late acceleration.

Lastly, study four was a case study on the effects of fixed trunk WR and randomly varying WR during a COD task, modified vector coding of pelvis-thorax inter-segment coordination revealed the highest coordination variability between segments in the randomly varying WR condition. COD times in this condition were also faster on average. Randomly varying WR between-repetitions may confer technical benefits through exposure to a variety of potentially beneficial movement patterns.

This thesis informs strength and conditioning coaching using WR by describing relationships between WR loading and subsequent movement patterns. Findings build on emerging complex systems-based pedagogical approaches in the field, which recognise the utility of execution variability and individualised interventions.

Student Declaration

I, Karl Trounson, declare that the PhD thesis entitled "Acute effects of lightweight wearable resistance on general athletic skill coordination among field-based athletes" is no more than 80,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work. I have conducted my research in alignment with the Australian Code for the Responsible Conduct of Research and Victoria University's Higher Degree by Research Policy and Procedures.

All research procedures reported in the thesis were approved by the Victoria University Human Research Ethics Committee HRE19-020.

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This table must be incorporated in the thesis before the Table of Contents.

Chapter No.	Publication Title	Publication Status • Published • Accepted for publication • In revised and resubmit stage • Under review • Manuscript ready for submission	Publication Details • Citation, if published • Title, Journal, Date of acceptance letter and Corresponding editor's email address • Title, Journal, Date of submission
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Publications

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Abbreviations and Symbols

°	Degrees
°/s	Degrees per second
±	Plus or minus
1RM	One repetition maximum
ANOVA	Analysis of variance
AP	Anterior-posterior
*bf*PCA	Bivariate functional principal component analysis
BW	Body weight
cm	Centimetres
COD	Change of direction
COM	Centre of mass
E	Rotational energy
EDF	Estimated degrees of freedom
EMG	Electromyography
FT	Fixed trunk
g	Grams
γ_i	Segment coupling angles
GAM	Generalised additive model
GRF	Ground reaction force
HAS	Heavy anterior shank
HAT	Heavy anterior thigh
HPS	Heavy posterior shank
HPT	Heavy posterior thigh
HKB	Haken-Kelso-Bunz
Hz	Hertz
I	Moment of inertia
J	Joules
kg	Kilograms
km	Kilometres

LAS	Light anterior shank
LAT	Light anterior thigh
LPS	Light posterior shank
LPT	Light posterior thigh
m	Metres
min	Minutes
ML	Medial-lateral
mm	Millimetres
ms	Milliseconds
$m.s^{-1}$	Metres per second
N	Newtons
N·m	Newton metres
N·s	Newton seconds
ω	Segment angular velocity
PCA	Principal component analysis
RS	Random segment
s	Seconds
SD	Standard deviation
SOM	Self-organising map
SPM	Statistical parametric mapping
™	Trademark
W	Watts
WR	Wearable resistance

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Chapter 1 – Introduction

Strength and conditioning coaching plays an increasingly prominent role in field-based sport athlete physical preparation as a means of reducing injury incidence and increasing action capabilities in general athletic skills such as running, jumping, accelerating, decelerating, and changing direction (Sousa 2019). Historically, coaches have typically set about achieving these endpoints through implementation of training modalities that maximise neuromuscular output. These have primarily included resistance, speed, and plyometric training and their variations (Sandler 2005; Gamble 2013; Baechle and Earle 2008). Importantly, influences from research biomechanics and applied track and field coaching have broadened the discipline's scope to include greater consideration for the contribution of technique to general athletic skill performance (Bobbert and van Soest 1994; McBride et al. 2002; Husbands 2013; Pfaff 2023). The increased focus on technique development has been accompanied by the need for implementation of best practice pedagogy. Where skill deconstruction and error minimisation around "gold standard" technical models have been commonplace, increasingly pedagogical approaches grounded in a complex systems perspective of human movement are being implemented (Davids et al. 2008b; Renshaw et al. 2010). Extensive research quantifying coordinative changes resulting from these interventions is required, however, particularly in relation to general athletic skills in field-based sport.

Complex systems theory describes the characteristics of complex systems, including dynamic interactions between components leading to emergent patterns of order, nonlinear relationships between inputs and outputs, and unpredictability (Boehnert 2018). Human movement has been demonstrated to exhibit these characteristics, which calls into question the use of prescriptive technical models and linear pedagogical approaches (Haken et al. 1985; Schmidt et al. 1990; Carson et al. 1995). Effective pedagogy from a complex systems standpoint incorporates several key themes. For instance, movement variability is embraced as a means of facilitating exposure to an array of potentially functional movement patterns (Chow et al. 2006b; Correia et al. 2019). Additionally, constraints may be implemented to set boundaries on or facilitate movement exploration (Chow et al. 2011; Bosch 2015).

Athletes are encouraged to focus on external movement effects rather than conscious control of movement (Wulf et al. 2010; Porter et al. 2015). Lastly, exposure to relevant information-movement couplings is emphasised (Holmberg 2009; Jeffreys 2011; Spiteri et al. 2018). Methodological frameworks grounded in one or more of these ideas, such as a constraints-led approach to motor learning, differential learning, and error amplification, have demonstrated positive outcomes when investigated in sport skill pedagogy (Newell 1985; Lee et al. 2014; Savelsbergh et al. 2010; Milanese et al. 2016; Gray 2020).

In strength and conditioning coaching, complex systems-based pedagogical approaches are increasing in popularity (Bosch 2015; Brearley and Bishop 2019; Kadlec et al. 2023; Dos'Santos and Jones 2023b). Implementation of constraints to shape emergent movement, e.g. sprinting over small hurdles to increase hip flexion (Kiely 2020), promote variability, e.g. varying plant leg approach velocities in a change of direction task (Nimphius 2017), or encourage an external focus of attention, e.g. jumping to reach a target (Makaruk et al. 2020b), attest to this point. In many instances, however, the specific coordinative changes brought about by constraint alteration are speculative and have not been thoroughly quantified. There is therefore a need for research into the effects of constraint implementation and manipulation on biomechanical process variables in general athletic skills, over and above the effects on task outcome measures alone.

Effectively innumerable possible constraints exist, which coaches may implement to direct movement or encourage variability. Lightweight wearable resistance (WR) attached to body segments is one example, and has seen a recent rise in application and research interest (Macadam et al. 2017b; Zhang et al. 2018; Macadam et al. 2021b; Feser et al. 2021b). Extensive investigation has been conducted into WR in relation to its effects as a mechanical overload stimulus, however, to date its utility as a constraint to influence coordination in a complex systems-based pedagogical framework has not been examined. Operationally, this requires a detailed analytical assessment of the effects of WR on coordination. Multidimensional, nonlinear time series data, inter-repetition variability, and individual-level responses should be considered (Hamill et al. 2000). In this way, a complex systems perspective is integrated across the WR implementation framework and the analysis of its impacts on coordination in general athletic skills. This thesis will specifically investigate the acute effects of WR on performance and coordination in overground running, early and late acceleration, and change of direction among field-based athletes. It is hoped that the findings of this thesis will continue to advance strength and conditioning coaching practices, particularly in relation to the use of WR and the implementation of complex systems-based pedagogical approaches.

Chapter 2 – Literature Review

2.1 Introduction

This review seeks to describe the emergence of strength and conditioning coaching for field-based sports as a professional discipline. The primary objectives of coaches within this field are then identified. These include enhancing performance of general athletic skills (i.e. running, accelerating, jumping, and changing direction) and managing risk of injury occurrence. With particular focus on the former objective, the evolution in approaches to achieving this aim are detailed. Broadly, there has been an expansion of scope from neuromuscular capacity development for facilitating force production and power output through traditional resistance training, to greater consideration for the technical elements that contribute to general athletic skill performance. This expansion has been accompanied by recognition of the need for best practice pedagogical approaches, many of which are grounded in a complex systems perspective of movement.

Rationale for the formal consideration of human movement as a complex system is provided, followed by a commentary on the existing applications of complex systems-based pedagogical approaches in sport skill development generally. A variety of pedagogical approaches are presented and discussed in the context of athlete skill level and the advantages of such approaches over more traditional coaching methods are explained. Emerging examples of implementation of complex systems-based pedagogical approaches in strength and conditioning coaching specifically are then provided. Throughout, the value of crossdisciplinary perspectives and appreciation for the complexity and interdependence of factors contributing to general athletic skill performance is emphasised.

Extending upon the emergence of complex systems-based pedagogical approaches in strength and conditioning, lightweight wearable resistance (WR) is introduced as a tool for use in this framework. WR can be considered a task constraint. In a behavioural context, constraints remove degrees of freedom and limit behaviours that may be adopted. Coaches can therefore strategically implement or manipulate constraints to increase the likelihood of certain (favourable) movement patterns being adopted. Alternatively, constraints such as WR may alter tasks such that established movement patterns are ‘destabilised’ and athletes must explore variable movement techniques to maintain a task outcome. WR also provides overload from a mechanical perspective, demonstrating potential multilevel effects on the athlete. In investigating the effects of WR on movement and performance of general athletic skills, analytical approaches that address the complexity of biomechanical responses are advocated. These may involve consideration of time series, quantification of movement variability, assessment of interactions between segments, and consideration of individual-level responses. Utilising these approaches further unifies analyses with the perspective of human movement as a complex system and the growing implementation of complex systems-based pedagogical approaches in strength and conditioning.

2.2 Strength and conditioning for field-based sports

Strength and conditioning coaches are tasked with designing and implementing training programs to develop the physical capabilities of athletes. Enhancing sport performance and preventing injuries are key endpoints herein (Kraemer 1990; Stewart et al. 2017). Athletes competing in field-based team sports, such as Australian Rules football, soccer, rugby, and American football, derive particular benefit from directed strength and conditioning coaching given the considerable physical requirements of match play (Bloomfield et al. 2007; Coutts et al. 2015; Wellman et al. 2016). In these sports, strength and conditioning programs largely seek to enhance general athletic skills, which may not be sport-specific but do augment performance (Swinton et al. 2014; Emmonds et al. 2019). These include movements such as running, accelerating, jumping, and changing direction (Wormhoudt et al. 2017).

2.2.1 General athletic skills in field-based sports

Dedication of training time to improving performance of general athletic skills follows from the belief that a relationship exists between these skills and competition performance. This relationship is largely treated as implicit among strength and conditioning coaches, with influential texts in the field often focusing on the effectiveness with which interventions improve athleticism without necessarily discussing sport performance outcomes (i.e., Hansen and Kennelly 2017; Baechle and Earle 2008). Interestingly, this assumption has been challenged by research failing to demonstrate a relationship between athletic ability and in-game success in soccer (Wilson et al. 2017; Wilson et al. 2020). It must be said, however, that these findings only applied among athletes within a given playing grade and athletic differences were observed between athletes in different grades (Wilson et al. 2017). Overwhelmingly, research does point to a relationship between general athletic skill performance and measures of technical skill, playing standard, or match performance (Gabbett et al. 2011a, b; Gabbett and Seibold 2013; Deprez et al. 2015; Robertson et al. 2015; Risso et al. 2017; Wing et al. 2020). This prompts the question of what training interventions coaches should apply to best develop general athletic skills. The following sections describe the emergence, strengths, and limitations of the prevailing approaches in the field.

2.3 Approaches to general athletic skill development

Formal employment of strength and conditioning coaches in field-based sports began around the 1970s in collegiate American football (Epley 2004). Early priorities of coaches, typically with bodybuilding or weightlifting backgrounds, centered around enhancing athletes' size and strength (Shurley et al. 2017). This was inspired in part by the success of Soviet Olympic teams and athletes known to devote training time to developing these attributes (Riordan 1980). As the discipline progressed, greater focus would be directed toward attempts to maximise the transfer of strength training interventions to performance of particular general athletic skills (Pedemonte 1981; Tkach and Rudisill 1983).

2.3.1 Emphasis on neuromuscular capacities

Identification of training targets for strength and conditioning coaches was shaped by several factors. These included operational definition of a strength and conditioning coach as being responsible for gym-based training interventions (Shurley et al. 2019), historical ties of the discipline to strength sports, and a well-established body of muscle and exercise physiology literature offering accessible insights into the neuromuscular demands of general athletic skills (Bosco and Komi 1979; Cheetham et al. 1986; Abernethy et al. 1990; Wiemann and Tidow 1995). Relatable concepts, such as muscle cross sectional area, motor unit recruitment, and rate coding could be considered both in relation to the familiar domain of strength training and in general athletic skills, allowing mechanisms of training transfer to be proposed (Fleck and Falkel 1986; Sale 1987; Häkkinen and Keskinen 1989). Exercise selection could bias development of specific neuromuscular factors in line with the requirements of a given athletic task. For example, identification of force production from rapid motor unit recruitment of the gluteus maximus and knee extensors as being important in the early phase of sprinting led to the proposal that speed-strength exercises for these muscle groups be included in strength training programs (Delecluse 1997).

Influential work by Siff and Verkhoshansky (Siff and Verkhoshansky 1993) also facilitated strength and conditioning coaches in identifying exercises for improving general athletic skills through their dissemination of an applied transfer framework. Their five laws of dynamic correspondence proposed that greater transfer between an exercise and a target task would occur if there was greater similarity of; (a) amplitude and direction of movement, (b) accentuated regions of force production, (c) dynamics of effort, (d) rate and time of maximum force production, and (e) regime of muscular work. True to the existing leanings of the discipline towards a focus on neuromuscular output, this subset of specificity dimensions emphasised kinetics, with arguably an underemphasis on positive transfer mediated through behavioural, technical, or kinematic dimensions. For instance, cueing an exercise with an analogy or manipulating athlete focus of attention can improve transfer without apparent changes to dynamic correspondence (Totsika and Wulf 2003; Hebert and Williams 2017; Makaruk et al. 2020a; Grgic et al. 2021). In another instance, mobility training may acutely increase joint range of motion and facilitate increased segment angular impulse during movements, giving rise to positive impacts on task performance despite little dynamic correspondence (Moran et al. 2009; Lee et al. 2015; Dallas et al. 2019). Centring the evaluation of exercise transfer around resistance exercise, in conjunction with coach preferences for interventions of this kind (Shurley 2013; Sousa 2019), likely distorted expectations of such interventions and underrepresented the complexity of factors influencing general athletic skill performance.

Although less closely studied from a transfer standpoint, technical training interventions would increasingly be implemented by coaches with growing appreciation for the contribution of technique to general athletic skill performance (Arthur and Bailey 1998; Dintiman et al. 1998).

2.3.2 Approaches to technique development

Extension of the discipline beyond maximising neuromuscular output appeared to be mediated both by deeper integration of biomechanics from a theoretical standpoint (Mann et al. 1984; Hay 1993; Bloomfield et al. 1994), and influences from track and field coaching on the applied side (Francis and Coplon 1991; Bompa 1999; Lentz and Hardyk 2000; Gambetta 2007). An example in the case of the former is work in which distinctions between total neuromuscular output and the temporal sequencing of motor unit recruitment in jump performance were effectively described (Bobbert and van Soest 1994). Researchers used forward dynamics, a technique in which motion is calculated from known temporal patterns of joint torques, to create a squat jump simulation model wherein the effects of alterations to the timing and magnitude of lower body muscle activity could be observed. In their model, greater magnitude of lower limb muscle activity, representing a gain in strength, led to decreased jump heights. This effect was reversed such that there was an increase in jump height when the model was reoptimised allowing for concomitantly altered timing of muscle activity. There are also similar findings *in vivo*. Following 8 weeks of jump squat training using 80% of a 1RM squat load, male athletic participants exhibited a 60% increase in the average vastus lateralis electromyography (EMG) output during jump squats (McBride et al. 2002). These changes were not accompanied by changes in jump height, however, suggesting that other factors such as intermuscular coordination contribute alongside neuromuscular output to the performance outcome. Inverse findings have also been demonstrated; namely that jump height can increase despite a reduction of EMG activity of the lower limb muscles (Wulf et al. 2010). Differences in intermuscular coordination may enable appropriate contraction sequencing and summation of forces to increase propulsion of the body in spite of lower total neural activation and contractile force of involved muscles (Bobbert and van Ingen Schenau 1988). For general athletic skills, such findings clearly support the need for consideration of training interventions aimed at improving technique.

Deterministic models would further unify strength and conditioning and biomechanics, and contribute to greater emphasis on technique interventions, through the mapping of kinetic and kinematic factors contributing to general athletic skill performance (Hay 1993; Bompa 1999; Deane et al. 2005; Cronin and Hansen 2006). These models describe the relationships between a movement outcome measure (e.g. sprint acceleration speed) and the biomechanical process variables that contribute to it (e.g. stride length and stride frequency), at several levels (Hay and Reid 1988). In the models, technical factors are situated alongside kinetic factors, suggesting at least some level of parity in terms of performance contributions (Hunter et al. 2004). Identification of kinematic determinants and associated performance implications provides coaches with clear technical training targets, thus facilitating inclusion of such interventions in athlete development programs (Bezodis et al. 2017; Dos'Santos et al. 2021a). For example, investigations would identify the meaningful contributions of abbreviated knee extension at toe-off (Murphy et al. 2003), long flight distance (Hunter et al. 2004), and high net horizontal ground reaction force (GRF) production (Morin et al. 2012), respectively, to sprint velocity assessed during sprint acceleration. These technical points have appeared subsequently in applied textbooks and coaching resources as concepts of "delayed knee extension" (Smith 2018; Moir et al. 2018; Pigg 2021; Oeppert et al. 2023), "projection" (Dodoo 2018; Grubbs and Dodoo 2022), and "forward lean" (Faigenbaum et al. 2020; Dos'Santos and Jones 2022). Although there is subjectivity in the selection of levels and inclusion of variables in deterministic models, translation of deterministic modelling research into applied coaching practice was likely a factor in solidifying the pursuit of athletic skill development through technique changes. Prior to this, shifts towards a technique focus within the discipline were mediated by coaches with technical expertise gained through track and field experience (Husbands 2013; Pfaff 2023).

Expansion of services of coaches with track and field backgrounds to work with field-based athletes on general athletic skills was seemingly accompanied by a level of technical emphasis normally only given to sport specific skills (Newman 2010; Mann and Murphy 2015). Coaches such as Vern Gambetta, Loren Seagrave, Ralph Mann, and Dan Pfaff would have substantial influence on strength and conditioning coaching practices through direct work with athletes, mentorship of and knowledge sharing with junior coaches, and engagement with large scale private athletic training facilities (e.g. Altis) (Husbands 2013; Bingisser 2016; Pfaff 2022). One consequence of this would be increased implementation of track and field-derived drills by strength and conditioning coaches (Brown et al. 2000; Stewart et al. 2020; Nicholson et al. 2022; Walker 2024). At scale, however, signal attenuation or the necessary simplification and systemisation of drills and training systems may have contributed to suboptimal implementation from a skill acquisition standpoint

(Hiserman 2010). This manifests in the form of skill deconstruction, error minimisation around prescriptive technical models, linear progressions, internal attentional cueing, and high feedback frequency.

"Wall drills", standing stationary arm swings, and A- and B-marches are common examples of sprint training deconstruction in line with a putatively ideal technical model (Cissik and Barnes 2004; Brown et al. 2014; Clark 2018; Nicholson et al. 2022). Skill deconstruction is underpinned in part by the belief that "*after all components are mastered individually in training, they can be reassembled to produce a successful race*" (Amneus et al. 2012). It is common for movement variability during training to be considered detrimental, or indicative of a lower skill level, while inter-repetition consistency is preferred (Amneus et al. 2012; Brown et al. 2014; Grace 2020). In addition, linear organisation of practice often predominates, e.g. technique work "*establishes and familiarizes the body with proper movement patterns for the proceeding drills. After proper movement patterns are established and rehearsed, speed of movement and reaction drills…are implemented"* (Clark et al. 2010b).

Many contemporary perspectives in skill acquisition, motor learning, and motor control view goal directed movement as an emergent characteristic of a complex system (Davids et al. 2014; Kelso 2017; Araújo et al. 2020). Such perspectives call into question the effectiveness of the coaching approaches described above (Wulf and Shea 2002; Davids et al. 2006a; Chow 2013). Just as historical integration of biomechanics contributed to progress in strength and conditioning coaching, recent steps to incorporate contemporary skill acquisition approaches have also begun to shape coaching practices (Bosch 2015; Brearley and Bishop 2019; Wild and Goodwin 2023).

In summary, where strength and conditioning approaches historically emphasised development of neuromuscular capacities through resistance training, increasingly there is focus on the technical components that influence general athletic skill performance. Observations that transfer of training is multifaceted and mediated by factors beyond kinetic overload contributed to this shift. In addition, integration of applied biomechanics and influential coaches with backgrounds in track and field have provided support for increased consideration of movement technique. This shift has necessarily been accompanied by the need for consultation of contemporary pedagogical approaches. These are often grounded in a complex systems perspective of human movement.

2.4 Human movement as a complex system

Traditional human movement theories largely assumed hierarchical control in which movement arose from, and was modulated by, a central controlling mechanism operating in a top-down fashion (Keele and Posner 1968; Lashley 1917). This was challenged by Bernstein (Bernstein 1967), who reasoned that an executive agent could not navigate the immense degrees of freedom arising from the many components of human movement. Instead, top-down and bottom-up processes appeared to cooperate to stabilise a collective order of the movement system. “Soft assembly”, i.e. flexible and temporary recruitment, of the components contributing to movement (neurons, muscles, cells, etc.) would eliminate redundant degrees of movement freedom to satisfy the demands of a task (Kugler and Turvey 1987). The resultant flexibility in motor control would allow a given movement to vary each time it was performed to negotiate a continually changing environment (Thelen 1995). Bernstein observed this experimentally among expert blacksmiths, who exhibited “repetition without repetition”, i.e. movement execution variability, when striking an anvil with a hammer (Bernstein 1967).

Although not explicitly termed by Bernstein, many of the human movement tendencies he described are indicative of a complex, adaptive system (Juarrero 1999). Complex systems theory describes characteristic features of complex systems, including emergence, self-organisation, nonlinearity, and unpredictability (Boehnert 2018). In relation to human movement, a complex systems perspective suggests that stable states of macroscopic order i.e., movement patterns, emerge from the dynamic interactions of many individual and environmental components (Clarke and Crossland 1985; Ottino 2003; Comfort 1994). This phenomenon can be modelled through dynamical systems theory, which describes the dynamic patterns of complex systems using nonlinear differential equations (Fuchs 2013). In experiments on the coordination of rhythmic, oscillating finger movements, participants exhibited an abrupt and spontaneous switch from an initially anti-phase pattern to an in-phase pattern as they increased oscillation frequency in response to a metronome (Kelso et al. 1981; Kelso 1984). Modelling of the so-called “order parameter”, in this case the phase difference between the fingers, as a function of the “control parameter”, in this case oscillation speed governed by metronome frequency, reflects how the stability of the relative phase changes with increased oscillation frequency. The Haken-Kelso-Bunz (HKB) model describes how at low oscillation frequency, the system has two stable coordination states, or “attractor states” – in-phase movement and anti-phase movement (Fuchs 2013; Haken et al. 1985). As frequency increases, the anti-phase pattern becomes unstable, leaving in-phase movement as the only stable coordination pattern, which explains the experimentally observed “phase transition”. Despite a linear increase in metronome frequency, the tipping point in movement occurs at a certain critical rate, which is indicative of movement as having nonlinear properties. Critically, the HKB model, and variations of it, have successfully been extended to describe coordination dynamics between nonhomologous limbs (Carson et al. 1995; Kelso and Jeka 1992) and even rhythmic movement between different people (Schmidt et al. 1990).

Because the movement system is “open” as far as receiving and outputting energy from and into the environment, the self-organisation tendencies adopted are shaped by both internal and external constraints on the system (Kugler and Turvey 1987). Effectively, constraints limit degrees of freedom, which narrows the behavioural trajectories that can be adopted (Thelen 1995). Newell’s (Newell 1986) theoretical model of constraints on action proposed that coordination patterns emerge during goal-directed behaviour as a result of the interplay between organismic, environmental, and task constraints. Organismic constraints pertain to an individual’s biological characteristics including physiological, psychological, and emotional attributes. Environmental constraints are physical variables external to the individual, such as light, temperature, and terrain. Task constraints relate to the goal of a particular motor task, rules associated with an activity, and activity-related equipment. By specifying categories of constraints, Newell provided a more detailed conceptualisation of the emergence of coordination patterns during goal-directed behaviour, which has informed skill acquisition and motor learning in practice (Davids et al. 2008b; Renshaw et al. 2010; Handford et al. 1997; Ko et al. 2003; Moy et al. 2020).

Another important theoretical concept stemming from a complex systems perspective is that of ecological dynamics (Araújo et al. 2006). This framework integrates the ideas of dynamical systems theory and constraints on dynamical systems previously described with

Gibson's (Gibson 1979) work on ecological psychology. According to Gibson, perception is tuned to specific information in the environment that affords actions relative to an individual's action capabilities (Gibson 1979). As an individual moves within an environment, the optical flow of information generated creates a "perception-action" cycle that regulates behaviour adaptively (Warren 1990). From an ecological dynamics perspective, movement self-organises from the continuous and dynamic interplay between an individual's action capabilities and the "affordances" or perceived opportunities for action in their environment (Gibson 1979; Davids et al. 1994).

2.4.1 Complex systems approaches in sport pedagogy

Prior to implementation by strength and conditioning coaches, the theoretical models outlined above have been applied, and their efficacy evaluated, in sport skill pedagogy (Davids et al. 2008b; Davids et al. 2006a; Chow et al. 2016; Renshaw et al. 2019). In detailing these applications, it is useful to refer to three stages of learning proposed by Newell (Newell 1985); namely coordination, control, and skill. In the coordination stage, beginners seek to establish basic relationships between components of the movement system to achieve functional, goal-directed movements. At the control stage, individuals are beginning to refine a functional coordination pattern through varying parameters such as velocity, force, and acceleration (Williams et al. 1999). This ultimately enables the coordination pattern to be applied in more dynamic and varied contexts. The skill stage is characterised by fluid, efficient, and functionally variable movement that reliably satisfies a task goal. Individual skill level influences the effectiveness of a given pedagogical approach. Strength and conditioning coaches must be mindful of this when applying these approaches for the development of general athletic skills.

For individuals at the coordination stage, skills are often deconstruction to reduce task complexity (Lewis and Granic 2000). Provision of extensive verbal feedback to direct movement and correct errors is also common (Chow et al. 2016). Although performance of isolated components may be achieved more quickly with this approach, the coordination required to execute these components often does not faithfully reflect that required to perform the whole skill (Davids et al. 2008b). In addition, instructional movement "correction" invokes an internal, conscious control mechanism, rather than the self-organising, implicit process understood to characterise complex systems like human movement (Correia et al. 2019). Examples of traditional, linear pedagogy of this kind can be readily found across sports including basketball, with learners instructed to have "*arms, elbows, and thumbs…at right angles*" when shooting (Krause et al. 2008), volleyball, with serving technique broken down into "*correct stance, toss, contact, and follow-through*" (Peterson 2006), and weightlifting, with 30 body positioning instructional steps described as part of the execution of a snatch movement (Baechle and Earle 2008).

In response to shortcomings of traditional pedagogy, contemporary skill acquisition approaches, which align with a complex systems perspective of human movement are increasingly utilised. Many of these approaches are encompassed in the theoretical framework of "nonlinear pedagogy", which is grounded in concepts of ecological dynamics (Chow et al. 2006b; Correia et al. 2019). Principles of nonlinear pedagogy include; (i) representative learning design to maintain the integrity of contextual factors in performer-environment interactions, (ii) development of relevant information-movement couplings, (iii) manipulation of task, environmental, or organismic constraints to set boundaries on or facilitate exploration of movement, or to alter/simplify tasks, (iv) embracement of functional variability as a necessary means of facilitating exploratory behaviour and in turn the emergence of individualised movement solutions, and (v) focus on external movement effects rather than conscious control of movement (Chow et al. 2006b; Correia et al. 2019). Superior outcomes as far as task performance and variety of movement strategies exhibited have been found when nonlinear pedagogical approaches have been compared against traditional pedagogy in tennis (Lee et al. 2014) and baseball hitting (Gray 2018).

A "constraints-led approach" to motor learning is the primary methodological framework used to apply principles of nonlinear pedagogy (Chow et al. 2021). In a constraints-led approach, constraints are deliberately manipulated to facilitate skill development (Renshaw et al. 2019). Appropriately implemented, a constraints-led approach can alter training environments to mimic competition, highlight critical information-movement couplings, increase the likelihood of adoption of certain movement patterns, allow exploration of movements for task execution in varied contexts, and direct attention to movement outcomes rather than processes.

Returning to the skill acquisition of an individual at the coordination stage, a constraints-led approach would favour implementation of constraints that afford certain functional movement behaviours (Davids et al. 2008b). These elements have been exemplified in a constraints-led approach to power clean technique (Verhoeff et al. 2018). Common movement strategies adopted by novices, which hinder performance at heavy loads, including excessive looping of the barbell away from the body and jumping forward to receive the barbell, were identified. Constraints in the form of upright poles placed in front of the barbell and a small ledge upon which participants stood when lifting were then incorporated during training. Participants altered movement technique in accordance with the intended effect of the constraints and this transferred to an improvement in lifting performance in two out of three cases. Although effective in this instance, the constraints-led approach does caution against implementing an excess of constraints that force an individual towards a putative idealised model of movement without respect for their unique intrinsic behavioural dynamics (Renshaw et al. 2019).

In the control stage, individuals have more stable and reproducible movement patterns, which are able to consistently satisfy a task goal within limited contexts (Davids et al. 2012). In this stage, coaches may seek to promote movement variability, such that the learner explores a wider range of possible task solutions, thereby expanding their action capabilities (Schöllhorn et al. 2006; Schöllhorn et al. 2009). Several complex systems-based pedagogical approaches can be utilised for this purpose (Lee et al. 2014). Again, a constraints-led approach has utility, however, rather than directing the learner's movement towards particular functional states, constraints may be manipulated to perturb or destabilise existing preferred patterns and promote exploitation of movement system degeneracy, facilitating task success across more varied contexts (i.e. adaptability) (Orth et al. 2017). By way of example, young tennis athletes exposed to changes in net height, target area, court size, and rules throughout a four week training period exhibited a greater number of forehand execution styles than their counterparts who received traditional, linear pedagogy (Lee et al. 2014).

In addition to a constraints-led approach, another complex systems-based pedagogical approach is differential learning. Differential learning is aimed at promoting exploration of movement patterns without attempting to guide or direct movement in a specific direction.

In this sense differential learning primarily addresses principle iv of nonlinear pedagogy – embracing variability to facilitate exploratory movement behaviour. This is achieved through deliberate incorporation of random noise (Schöllhorn et al. 2010a; Savelsbergh et al. 2010; Santos et al. 2018). The rationale in this case is that adding random movement variation during a task leverages the stochastic resonance phenomenon wherein noise may improve the detection of weak but functional signals within the motor system (Schöllhorn et al. 2009). Movement variation is achieved through alterations to constraints or instructions, and random scheduling is used wherein the alterations change on a repetition-to-repetition basis. This approach is proposed to enhance the learner's identification and utilisation of relevant motor and sensory information for successful task execution (Henz and Schöllhorn 2016). New domains of coordinative stability may emerge through this process, thereby consolidating performance. In practice, for an athlete developing their baseball hitting skill for example, rather than instruction towards a technical model, they may instead be exposed to random repetition-to-repetition variations in body posture, bat position, pitch height, and pitch speed (Gray 2020). Promising results from this approach in terms of performance improvements have been demonstrated in baseball (Gray 2020), as well as in soccer skills (Santos et al. 2018) and speed skating (Savelsbergh et al. 2010).

Amplification of error may also be a complex systems-based pedagogical approach with utility during the control stage. In this approach, learners are directed to exaggerate undesired technique characteristics to amplify the negative performance outcomes from their movement (Milanese et al. 2008). This then informs implicit error correction across subsequent repetitions. Positive outcomes of such an approach have been demonstrated in a standing long jump (Milanese et al. 2008), golf (Milanese et al. 2016), and weightlifting (Milanese et al. 2017), however, it is worth noting that this type of approach still relies on defining a preferred technical model against which movement errors are judged.

At the skill stage, greater emphasis may be placed on higher level environmental perceptual attunement than individual action capabilities (Seifert et al. 2014b). Constraint manipulation in this context can foster an athlete's ability to recognise affordances that appropriately match their action capabilities (Davids et al. 2015). Diverse exposure to such instances can improve performance by promoting creative problem solving, as well as deepening understanding of interpersonal dynamics in a team context (Woods et al. 2020a). As one example, Woods et al., applied informational (environmental) constraints of a narrow score margin and little remaining time to Australian Rules football match simulations (Woods et al. 2020b). Players on the leading team were therefore encouraged to attune to player density cues for safer passing options, while players on the trailing team sought out opportunities for dynamic and fast play. Changes in actions were commensurate with these shifts in attunement. As with complex systems-based pedagogical approaches applied to the other stages of learning, the use of repetitive practice of predefined techniques is deemphasised at the skill stage. Varied, context-specific practice that reflects the complexity of competitive performance environments is suggested for superior performance benefits (Maloney et al. 2018).

Naturally, there is considered to be overlap between stages of learning and ongoing skill development may warrant periodic (re)implementation of different pedagogical approaches, particularly once a period of skill stability is reached (Peh et al. 2011; Farrow and Robertson 2017). This is especially true if the local movement attractor states settled on are likely to be injurious or are limiting task success (Glazier and Mehdizadeh 2019).

Given the strengths of modern complex systems-based pedagogical approaches, there have been growing attempts to integrate these approaches into strength and conditioning coaching (Kiely 2011; Bosch 2015; Nimphius 2017; Brearley and Bishop 2019; Wild and Goodwin 2023).

2.4.2 Complex systems-based pedagogy in strength and conditioning

Several concepts grounded in a complex systems perspective of human movement and skill development have increasingly been advocated for and applied in strength and conditioning coaching in recent years. These include nonlinear training structure, manipulation of constraints to influence movement strategies, promotion of movement execution variability, external cueing and provision of knowledge of results, and implementation of representative learning design.

From a training structure standpoint, Kiely's (Kiely 2011) description of dynamic adaptive planning for physical performance emphasised the importance of a flexible, individualised approach to training over a rigid periodised plan given inevitable heterogeneity of responses to training between athletes. This is noteworthy given the historical popularity of linear and block periodisation (Bompa 1999). More recently, a “mixed-methods approach” to exercise selection has been proposed to maximise transfer of training (Brearley and Bishop 2019). This approach suggests a mix of strength capacity development through a “traditional overload approach”, i.e. general strength exercises, and movement technique development through a “coordinative overload approach”. Coordinative overload in this instance refers to training principles described by Bosch (Bosch 2015), which involve implementation of variations to a target task such as sprinting. Variations are typically prescribed as progressions from more highly constrained and less representative, e.g. fast limb switch step ups, to relatively less constrained and more representative, e.g. sprinting with a dowel held overhead (Brearley and Bishop 2019). Key in all instances, however, is that the pattern of muscular recruitment, sensory input, and intention remain similar to the target task, and that task constraints are manipulated to direct athletes toward certain defined attractor states (Bosch 2015).

Bosch’s development and promotion of a training system, which uses constraint manipulation to “stabilise” attractor states associated with general athletic skill performance, has inspired similar applications among numerous coaches (Dodoo 2018; Barone 2021; Tobin 2023). While this represents a step forward from a pedagogical standpoint, it must be acknowledged that there is subjectivity in Bosch’s approach to determining both suitable attractor states and constraints that promote their emergence. Indeed, Bosch concedes that “*movement attractors are relatively abstract principles of movement*”, but proposes that “*structures that are at risk, such as…the hamstrings when running, should preferably be in an attractor state*” during dynamic athletic actions (Bosch 2015). Analytical techniques derived from dynamical systems theory present a future path for more objective determination of movement attractors, with promising examples from walking (Kang and Dingwell 2008; Raffalt et al. 2020) and running (Weich and Vieten 2020; Vieten and Weich 2020). However, questions remain about the suitability of categorising attractor states given the substantial variation in movement execution between even high level athletes, as well as the impact of unique individual intrinsic dynamics (Glazier and Mehdizadeh 2019).

Questions over the generalised recommendations of movement attractors aside, Bosch proposes that hip lock, swing leg retraction, and trunk extension during rotation are examples of necessary attractor states for optimal change of direction performance (Bosch 2015, 2020). Developing the hip lock attractor state, which refers to a single leg stance with the pelvis raised on the free/swing side, is achieved through prescription of tasks with constraints that require this movement for successful execution. Beginning with more confined tasks, the athlete may perform a single leg barbell clean movement while attempting to delay foot contact on a box placed in front of them. Hip lock is an emergent feature in the execution of this task if foot contact is sufficiently delayed. Progression may involve increasing action fidelity, e.g. sprinting with weight held as high as possible overhead. Through this approach to exercise prescription, elements associated with the identified attractor state are emphasised continuously across a phase of training, thus theoretically maximising transfer to change of direction performance.

Other proponents of a constraints-led framework in strength and conditioning have adopted slightly different approaches (Moir et al. 2018; Rice and Nimphius 2020; Kadlec et al. 2023). These include interpreting task constraints as the mechanical limitations to a desired action (e.g. sprinting (Moir et al. 2018) or dancing (Rice and Nimphius 2020)). Resistance training interventions are then prescribed to attenuate the associated organismic constraints, e.g. increasing ankle stiffness (organismic constraint) to facilitate a rapid rise in GRF (task constraint) during foot strike, thus enhancing sprint performance. Another approach is in the manipulation of task constraints to systematically increase exposure to some neural or musculoskeletal stimulus (Kadlec et al. 2023). Varying the presence, source, and timing of specifying information during a change of direction task alters peak knee valgus moment, which has implications for injury prevention training (Lee et al. 2013). This highlights the important notion that any alteration to task constraints invariably leads to interdependent changes in whole body kinematics and kinetics. Understanding and exploiting the directionality of these changes is a key means through which coaches can develop athlete coordination and train specific neuromuscular qualities.

Movement variability is also increasingly being leveraged in strength and conditioning coaching (Moras et al. 2018; Eaton 2021; Kadlec et al. 2023; Dos'Santos and Jones 2023b). Just as in complex systems-based sport pedagogy at the control stage of learning, altering constraints to perturb coordination when training general athletic skills has the potential to accelerate motor learning and facilitate adaptability in performance. While Bosch proposes a granular approach in which perturbations are selectively applied to more or less stable components within a movement (Bosch 2015), others suggest more general task variations in training (Nimphius 2017; Eaton 2021; Dos'Santos and Jones 2023b). Through variation, exposure to the sensori-motor landscape associated with a general athletic skill is maximised and familiarity with contextually useful coordination patterns is developed, similar to a differential learning approach. The ability to exhibit both strategic variability, i.e., utilising different methods to perform an action, such as a 1-foot versus 2-foot jump, and execution variability, i.e. subtle differences in coordination within a given method, appears to be a hallmark of higher performing athletes (Davids et al. 2015; Sayers et al. 2017; Orth et al. 2018). These abilities also may attenuate injury risk associated with general athletic skills (especially those performed repeatedly) by distributing demands across a wider variety of structures (Bartlett et al. 2007; Hamill et al. 2012; Nordin and Dufek 2019). With respect to the interdependence of factors that strength and conditioning coaches must consider, it may be the case that greater neuromuscular capacity (e.g. strength) expands the possible movement options for a given task, while fatigue, pervious injury, or high task complexity limit the potential for strategic and execution variability (Nordin and Dufek 2016; Nohelova et al. 2021; Morral-Yepes et al. 2023). The feedback and cueing style adopted by coaches can also impact on execution variability and performance more broadly (Wulf 2013).

A critical consideration in pedagogy is the type and frequency of instruction or feedback provided to the learner. As previously alluded to, prescriptive, internally directed instructions have typically predominated in technical training of general athletic skills. Instructions such as "elbow flexed to 90 degrees" and "low heel recovery" during sprinting (Baechle and Earle 2008; Dawes and Roozen 2011; Brown et al. 2014) relate to the movement pattern rather than movement outcomes, which appears to negatively impact performance acutely in accordance with the constrained action hypothesis (Wulf et al. 2001; Wulf 2007). For fast, reflexive, and largely subconsciously regulated actions in particular (e.g. sprinting), instructions or cues that direct attentional focus externally are preferable as automatic control mechanisms are preserved to a greater extent (Wulf et al. 2010; Porter et al. 2015). This is advantageous not just for task performance but also motor learning, particularly when skill level is low (Lohse et al. 2012; Winkelman 2017). Encouraging an external focus of attention also aligns more closely with a complex systems view of movement, wherein greater freedom for individual self-organisation of coordination is permitted (Davids et al. 2008b). This approach is being increasingly implemented in strength and conditioning during training of change of direction and acceleration (Benz et al. 2016; Nimphius 2017; Winkelman 2020; McNicholas and Comyns 2020). For feedback following a task, a similar duality exists between provision of knowledge of performance (feedback relating to movement process or technique) and knowledge of results (information about task outcome e.g. sprint speed). High frequency, descriptive knowledge of performance feedback commonly observed in strength and conditioning coaching may cloud working memory, create coach dependence, and be subject to the bias of a coach's preferred technical model (Weeks and Kordus 1998; Schmidt and Lee 2011; Winkelman 2017). A more nuanced approach in which the coach guides the learning process through selective dissemination of knowledge of results and carefully selected prescriptive knowledge of performance (possibly attuned to through manipulation of task constraints) is recommended (Otte et al. 2020; Oppici et al. 2021).

In strength and conditioning coaching, representative learning design has been utilised for some time, particularly in relation to training agility (Holmberg 2009; Jeffreys 2011; Spiteri et al. 2018). This appears to have followed specifically from work highlighting the dependence of agility performance on perception (Verstegen and Marcello 2001; Farrow et al. 2005). Emphasis on preservation of perceptual cues in training of other general athletic skills, such as sprint acceleration or jumping, has not occurred to the same extent, though there are growing calls for this to be considered (Yearby et al. 2022; Caldbeck and Dos'Santos 2022). It may be the case that coaches consider sport specific training and competition a sufficient means of enabling positive transfer of strength and conditioning training interventions. However, just as structuring practice drills to achieve exposure to certain volumes of movements (e.g. high speed running distance) is commonplace, representative drill designs in which maximal effort sprints, jumps, or decelerations are afforded, for example, could also be effectively utilised by strength and conditioning coaches. Such drills may serve as useful progressions beyond the development of action capabilities in non-representative contexts. However, as ecological validity of drills is increased, coaches must be prepared for inevitable nonlinear interactions between affordance detection, technical expression, and neuromuscular demands, which may complicate the predictability of training outcomes.

In summary of this section, recent integration of complex systems perspectives has furthered the discipline of strength and conditioning by highlighting; the dynamic interplay between factors contributing to performance, the utility of constraints to direct emergent movement behaviour, the value of movement variability in learning, and the need to consider individual behavioural dynamics and responses to interventions. Given the expansiveness of themes associated with the application of complex systems-based pedagogy to strength and conditioning, numerous areas of possible further investigation exist. This thesis will investigate specifically how lightweight wearable resistance (WR) – an increasingly popular training tool – may be used within a complex systems-based pedagogical framework to alter or improve coordination and performance of general athletic skills.

2.5 Lightweight wearable resistance

The practice of applying resistance to the body of an athlete undertaking sporting movements is extensive and well researched (Cronin and Hansen 2006; Alcaraz et al. 2018; Macadam et al. 2022; Bertochi et al. 2024). It is proposed that a balance between overload and specificity in which action fidelity is largely retained creates high likelihood of positive transfer (Alcaraz et al. 2008; Rumpf et al. 2016). In fact, it is often advised that addition of resistance not exceed the point beyond which movement technique begins to change (Spinks et al. 2007; Paulson and Braun 2011; Behrens and Simonson 2011). This heuristic is contestable, as the direction of technique change could in fact facilitate superior performance (Cahill et al. 2020; Osterwald et al. 2020). Suffice to say that between changes to neuromuscular output and technical factors there are many pathways through which positive transfer could be mediated. There are also many possible modalities of resistance (Cronin and Hansen 2006). Limb loading involving the attachment of weights to particular body segments to increase segment inertia has seen a rise in research and practical interest with the development of WR technologies such as the the Lila™ Exogen™ exoskeleton suit, Ironman Club KW-505 wrist and ankle weights, and W8FIT wrist and shank weights (Macadam et al. 2017b; Zhang et al. 2018; Macadam et al. 2019b; Uthoff et al. 2020; Hurst et al. 2020; Simperingham et al. 2020; Macadam et al. 2020a; Macadam et al. 2020b; Uthoff et al. 2021; Macadam et al. 2021b; Feser et al. 2021a; Feser et al. 2021c; Feser et al. 2021b; Macadam et al. 2021a; Busch et al. 2022; Akatsu et al. 2022; Feser et al. 2023).

The extensiveness of recent research into limb WR in general athletic skills owes to the many possible lines of investigation arising from different combinations of athletic skills, load magnitudes and configurations, and potential process variables. Early and late sprint acceleration have received the most attention (Macadam et al. 2017b; Zhang et al. 2018; Macadam et al. 2019b; Simperingham et al. 2020; Uthoff et al. 2020; Uthoff et al. 2021; Macadam et al. 2021b; Feser et al. 2021c; Feser et al. 2023), followed by maximal velocity sprinting (Simperingham and Cronin 2014; Feser et al. 2018b; Hurst et al. 2020; Macadam et al. 2021b), jumping (Macadam et al. 2017c; Bustos et al. 2020), and change of direction (Ryan et al. 2024). Without detailing the specific findings of each study, many of which are discussed in ensuing chapters, it is worth noting that the process variables analysed typically frame (or perhaps limit) proposed mechanisms of transfer. Stepping back further, selection of process variables likely reflects a bias towards metrics that are more readily attainable, analysable, and interpretable. Within the studies identified, whole body spatiotemporal measures are the most common process variables considered, followed by whole body kinetic measures, then joint-level kinetic and kinematic measures. Discrete measures are also more common, with very limited consideration for continuous, time series data (Feser et al. 2021c). Simperingham et al.'s (Simperingham et al. 2020) study on thigh and shank WR in sprint acceleration illustrates the point being made. The authors collected and analysed outcome measures (e.g. sprint time), discrete whole body spatiotemporal measures (e.g. flight time and ground contact time), and discrete whole body kinetic measures (e.g. peak horizontal GRF). Their conclusion was that WR has utility for developing sprint acceleration performance based on its "overload" effects on ground contact time (i.e. increased ground contact time) and step frequency (i.e. decreased step frequency), and its effect of increasing relative theoretical maximum horizontal force. While perhaps accurate, the culmination of many studies employing similar process variable selection (Macadam et al. 2017b; Macadam et al. 2017c; Dolcetti et al. 2019; Macadam et al. 2019b; Macadam et al. 2020b; Simperingham et al. 2020; Uthoff et al. 2020; Couture et al. 2020; Macadam et al. 2020a; Uthoff et al. 2021; Feser et al. 2021b; Feser et al. 2021a; Acker et al. 2022; Ryan et al. 2024) has been a body of research that seemingly underemphasizes potential positive transfer from WR mediated through effects on joint-level kinematics. The potential of WR for improving performance through technique changes therefore does not appear to have been sufficiently explored.

Many studies of WR assume *a priori* that changes to technique are deleterious to positive transfer (Macadam et al. 2017b; Feser et al. 2019; Simperingham et al. 2020; Uthoff et al. 2020; Uthoff et al. 2021). Kinematics are often included in analyses primarily to define breakpoints in loading magnitude, which coaches should avoid going beyond (Macadam et al. 2017b; Simperingham et al. 2020). One idea that has been raised is that WR may improve the "piston-like" action of the legs during acceleration (Macadam et al. 2019a; Macadam et al. 2020b). The theme entailed in this idea that WR could be used to positively influence movement technique is at the centre of what the present thesis seeks to explore.

Given the descriptions of complex systems-based pedagogical approaches provided hereto, it is reasonable to propose that WR could be utilised in these frameworks as a task constraint or movement control parameter. WR may direct movement towards patterns that benefit performance or induce movement variability generally, promoting exploration of techniques and adaptability. Chartering how WR can be used by strength and conditioning coaches as a pedagogical tool will ultimately require investigation into its effects on coordination and movement variability across several general athletic skills at individual- and group-levels, and in relation to acute and long-term exposures. This thesis will begin the exploration process by examining the effects of acute WR exposure on performance, coordination, and movement variability at the individual level across a number of general athletic skills. Appropriate analytical techniques are required to quantify these effects. In keeping with the complex systems perspectives discussed, analytical approaches that capture or retain dynamic properties of the data are advantageous. This includes preservation of temporal features, addressing nonlinear relationships, quantification of variability, and analyses of coordination between segments or at the whole-body level.

2.6 Analytical techniques

Biomechanical kinematic data seek to capture outputs of the movement system, which evidently has the features of a complex system (Davids et al. 2003b). As such, analytical techniques that can describe nonlinear relationships between inputs (e.g. WR application) and outputs (e.g. movement during general athletic skill performance), as well as the dynamic interactions between system components (e.g. body segments) are advantageous (van Emmerik et al. 2016). Given the pedagogical context in this instance, analyses that quantify movement stability and variability provide further value (Hamill et al. 2000). Employing a range of analytical approaches across multiple dimensions of data should offer a more nuanced perspective into the effects of WR on movement and performance of general athletic skills.

Exemplifying an approach to nonlinear data, generalised additive modelling has been applied to the changes in lower body joint angles over time during running among novice and experienced runners (Harrison et al. 2021). This approach uses smooth basis functions (e.g. splines) to flexibly model the data (Pedersen et al. 2019). By including the experience level as a factor and interaction terms between group and time in the model, joint-level kinematic differences between the groups across the stance phase could be determined. This provided a high resolution perspective of the differences in movement organisation based on experience level. Novices exhibited greater knee abduction and internal rotation, and less hip adduction than experienced runners during mid stance specifically, which may explain in part the increased injury risk observed among this group (Harrison et al. 2021).

Handling multi-dimensional time series data presents challenges, which have commonly been circumvented by extraction of discrete measures (e.g. peak, threshold, or mean values) (Balagué and Torrents 2005). Self-organising maps offer a means of reducing time series kinematic data from many body joints and planes of motion to two-dimensions for assessment of whole body coordination (Bauer and Schöllhorn 1997; Schöllhorn and Bauer 1998; Sarvestan et al. 2020). This technique has enabled the progression of movement technique at the whole body level within individual discus throwers across repetitions to be mapped, allowing for determination of within- and between-session movement consistency (Bauer and Schöllhorn 1997).

Assessment of movement variability is also of particular relevance given its potential value in a motor learning context. Several studies have considered variability in relation to joint couplings, thereby synthesising information about movement between neighbouring joints and the variability of these interactions (Pollard et al. 2005; Needham et al. 2014; Estevan et al. 2016; Maddox et al. 2020). Application of a variance measure, e.g. standard deviation, to a vector coding technique in which the orientation of vectors between successive points on angle-angle plots is calculated, provides this information. This approach has enabled demonstration that female college soccer players exhibit less variability in several lower body joint couplings across trials during a 45 degree change of direction task (Pollard et al. 2005). This could contribute to the higher injury incidence observed among female athletes during change of direction actions. In the context of WR, this type of analytical approach could be used to investigate whether WR application induces greater movement variability during performance of general athletic skills.

For practical purposes, capturing nonlinear dynamics in movement changes, e.g. using generalised additive modelling, upon implementation of an intervention such as WR may enable detection of subtle variations in joint movements that could be missed by linear modelling or the "coach's eye". Using self-organising maps to handle multi-dimensional time series offers a broad, yet detailed assessments of coordination and its changes in response to an intervention. This can draw coaches' attention to conditions under which movement is more stable or more variable, and which specific portions of a movement are most affected. Vector coding can provide insights into joint coupling and the variability herein. This offers insight to coaches about whether an intervention is limiting movement options or promoting exploration of different joint coupling sequences. Manipulation of the intervention may then take place in response to what is observed in order to alter variability levels.

In strength and conditioning, Wild et al.'s (Wild et al. 2022) analytical approach to athlete profiling in sprint acceleration provides a view into the emerging unification of contemporary perspectives on human movement, biomechanical analyses, and pedagogy within the discipline. Recognising the need to move away from a one-size-fits-all coaching approach, while also considering data interpretability and coach end-users who may service large athlete cohorts, Wild et al., put forward a whole-body kinematic profiling approach. This involved normalisation, ratio calculation and cluster analysis of sprint spatiotemporal variables to define four movement strategies with clear technical features. Using this, coaches can profile their athletes along the defined dimensions with data from increasingly accessible kinematic assessment technologies (McMillan 2021a, b; Kormis 2023). This is useful for selecting technical interventions, identifying subgroups of athletes who may have similar spatiotemporal characteristics and better or worse performance outcomes, assessing repetition-to-repetition consistency of movement strategy adoption, and even potentially identifying tissues at risk of injury (Wild 2022). Critically, Wild et al. advocate that coaches use complex systems-based pedagogical interventions, e.g. constraints-led approach and error amplification, use of external instructions, and respect for athlete self-organisation (Wild 2021a, b; Wild et al. 2022). It is on this emerging unification of complex systems approaches in strength and conditioning coaching that this thesis seeks to focus, specifically in relation to WR.

2.7 Conclusion

This literature review describes the evolution of strength and conditioning in field-based sports from a focus on enhancing neuromuscular capacities through traditional resistance training, towards a greater focus on technique to maximise general athletic skill performance, and finally towards contemporary pedagogical approaches to facilitate technical changes. WR is a training tool with possible applications in these contemporary pedagogical frameworks, whether through directing movement towards adoption of particular states or inducing movement variability. However, there have been no thorough investigations to date into how WR acutely alters coordination in general athletic skills among field-based athletes. An investigation of this type using analytical approaches that preserve complex and nonlinear elements of data will offer starting points for coaches seeking to use WR to influence technique in applied settings. This work will also further promote complex systems perspectives in strength and conditioning coaching and movement evaluation.

2.8 Aims

The overarching aim of this thesis is to describe the acute effects of WR on coordination and performance of general athletic skills among field-based sport athletes. The specific aims are to:

- Describe relationships between particular WR configurations and the expression of movement patterns during overground running, early and late acceleration, and change of direction actions.

- Determine the impact of WR on performance of early acceleration, late acceleration, and change of direction.
- Utilise analytical approaches aligning with a complex systems perspective of movement to describe (nonlinear) changes in coordination and quantify movement variability induced by WR.

The practical applications of this research are:

- Advancement of strength and conditioning coaching practices, particularly in relation to the use of WR, by building on existing complex systems-based pedagogical approaches in the field, which recognise the utility of execution variability and individualised interventions.
- Increased consideration for analyses of dynamic interactions between segments, nonlinear changes to movement, and domains of movement stability in general athletic skill assessments. These approaches are likely to be a growth area in biofeedback, particularly with increasing accessibility of motion capture technology.

Chapter 3 – Effects of acute wearable resistance loading on overground running lower body kinematics

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RESEARCH ARTICLE

Effects of acute wearable resistance loading on overground running lower body kinematics

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Abstract

Field-based sports require athletes to run sub-maximally over significant distances, often while contending with dynamic perturbations to preferred coordination patterns. The ability to adapt movement to maintain performance under such perturbations appears to be trainable through exposure to task variability, which encourages movement variability. The aim of the present study was to investigate the extent to which various wearable resistance loading magnitudes alter coordination and induce movement variability during running. To investigate this, 14 participants (three female and 11 male) performed 10 sub-maximal velocity shuttle runs with either no weight, 1%, 3%, or 5% of body weight attached to the lower limbs. Sagittal plane lower limb joint kinematics from one complete stride cycle in each run were assessed using functional data analysis techniques, both across the participant group and within-individuals. At the group-level, decreases in ankle plantarflexion following toe-off were evident in the 3% and 5% conditions, while increased knee flexion occurred during weight acceptance in the 5% condition compared with unloaded running. At the individual-level, between-run joint angle profiles varied, with six participants exhibiting increased joint angle variability in one or more loading conditions compared with unloaded running. Loading of 5% decreased between-run ankle joint variability among two individuals, likely in accordance with the need to manage increased system load or the novelty of the task. In terms of joint coordination, the most considerable alterations to coordination occurred in the 5% loading condition at the hip-knee joint pair, however, only a minority of participants exhibited this tendency. Coaches should prescribe wearable resistance individually to perturb preferred coordination patterns and encourage movement variability without loading to the extent that movement options become limited.

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Introduction

Across many field-based sports, athletes must be capable of running long distances throughout a match [1–3]. Depending on the sport, total running distance can range from an average of 6 km in rugby league to 12 km in Australian Rules football [1]. In Australian Rules football, soccer, rugby league, and rugby sevens, most of the distance covered during match play can be classified as "low-intensity activity", i.e., occurring at velocities <5.4 m.s^{-1} [1, 3]. While high-intensity efforts are often associated with significant match events, adequate sub-maximal running capabilities are also important for effective opponent tracking and retention of team formations during different phases of play throughout a match [4]. As such, training aimed at developing sub-maximal overground running performance is evidently worthwhile.

Development of sub-maximal running performance for field-based athletes is a multifactorial proposition and requires training of aerobic capacity, biomechanical factors for superior economy, and muscular strength [5–8]. Coaches should address these factors in training prescription and, in addition, athletes' ability to adapt their running coordination patterns in accordance with the dynamic constraints of the sport [9, 10]. The capacity to exhibit "adaptability" in this sense allows for greater maintenance of performance in varied contexts and is a hallmark of higher performing athletes in many sports [10–13]. In field-based sport, organismic constraints in the form of local metabolite accumulation from intermittent anaerobic efforts [14, 15], muscle damage arising from high force eccentric contractions during decelerations [16], and muscular contusion from compressive force impacts [17], all present scenarios in which there is a challenge to an athlete's preferred running coordinative structure, which must be adapted to.

Critically, the implementation of a training intervention aimed at encouraging movement variability in diving [10] suggests that the capacity for athletes to harness movement system degeneracy to maintain a performance outcome is trainable. This notion is further supported by nonlinear pedagogical training interventions in youth tennis [18]. Individuals exposed to greater task variability during training displayed a greater number of unique movement clusters, indicating the presence of degeneracy, during performance tasks. Exposure to task variability drives exploration of alternate movement strategies, or movement variability, as movement is adjusted to satisfy novel task demands [19]. Training in this way affords individuals the ability to adapt movement to maintain task performance under the varied constraints occurring in the dynamic sporting environment [10, 18, 20].

In the context of sub-maximal running kinematics, the effects of deliberately induced task variability through perturbation have been explored in research using elastic tubes attached from the hips to the ankles [21–23]. This intervention increases joint kinematic variability acutely, after which there is relatively rapid stabilisation around a slightly shifted coordinative structure [21, 23]. Although no post-training running test under novel conditions was undertaken, the performance benefits associated with exposure to constraints, which encourage movement variability in this way, are widely reported [24–28].

It is also worth noting that analyses of kinematic variability induced by constraint implementation to date have typically focussed on group-level changes [21, 29, 30]. Increasingly, there is support for individual-level consideration given that intrinsic behavioural dynamics and baseline kinematic characteristics alter the extent to which a particular constraint is experienced as a perturbation to the system [31–33]. Kinematic changes may vary markedly between individuals, which may not be clear when considering generalised responses, yet is important in a practical setting [34–36].

Lightweight wearable resistance (WR) may be a useful training tool for encouraging exploration of movement system degeneracy through movement variability. WR involves attachment of small weights to particular body segments, such as the trunk, arms, thighs, and shanks [37]. To date, research has considered WR in its capacity as a movement specific overload stimulus [38, 39], however, WR also presents a perturbation to coordination, which may induce movement variability. WR application alters segment inertial properties and as such can be considered an organismic constraint [40, 41]. Exposure to WR may ultimately be a useful stimulus for developing adaptable movement behaviours among athletes in preparation for changing organismic constraints faced during match play. This study aimed to describe the extent to which different acute lower limb WR loadings (1%, 3%, and 5% of body weight) alter coordination and induce movement variability during sub-maximal overground running. By considering both group- and individual-level responses, findings will provide context for coaches seeking to promote movement variability without imposing an excessive perturbation that limits movement options.

Materials and methods

Participants

Fourteen participants (three female and 11 male; mean ± SD: age 28.3 ± 4.4 years; height: 179.9 ± 7.6 cm; body mass: 76.8 ± 6.1 kg) volunteered to participate in this study. Participants were included on the basis that they were currently undertaking, or had recent previous experience (past year), in structured field-based sport competition. Participants in the study had no prior experience with WR. All participants provided written informed consent and were free from injury at the time of testing. All procedures used in this study complied with the criteria of the declaration of Helsinki and the ethical approval granted by the Victoria University Human Research Ethics Committee.

Procedure

Data collection apparatus. A 10-camera VICON motion analysis system (T-40 series, Vicon Nexus v2, Oxford, UK) sampling at 250 Hz was used for collection of kinematic data. A total of thirty-six reflective markers with 14mm diameter were attached to lower body landmarks on the pelvis, thighs, shanks, and feet according to the Plug-In-Gait model (Plug-In-Gait Marker Set, Vicon Peak, Oxford, UK) (Fig 1).

Wearable resistance. Throughout testing, participants wore Lila^{TM} Exogen^{TM} (Sportboleh Sdh Bhd, Kuala Lumpur, Malaysia) compression shorts and calf sleeves. During WR exposure trials, a combination of 50, 100, and 200g fusiform shaped loads (with Velcro backing) totalling the required proportion of participants' body weights were attached to the compression garments (Fig 2). Loads were distributed in a 2:1 thigh:shank ratio about the centre of mass of each segment [42]. The required loads were added in an alternating fashion between the anterior and posterior surfaces, and between a proximal-dominant and distal-dominant orientation, in order to avoid a large shift in the centre of mass of each segment.

Experimental setup. Testing was undertaken on a 20 m section of the Biomechanics Laboratory at Victoria University. Motion analysis cameras were arranged around the 10 m mark of the 20 m section and the approximate capture volume was 6.0 m long, 2.5 m high, and 3.0 m, wide.

Data collection. Following application of compression garments and attachment of reflective markers, participants undertook an initial warm-up in which they ran back and forth along the 20 m section in a "shuttle" fashion for 2 min. Running velocity was dictated through the use of an audible metronome, which counted each second from 1–9, before repeating for every subsequent shuttle. Participants underwent a 2 min rest period following the first warm-up run before performing a second warm-up run for 1 min at an increased

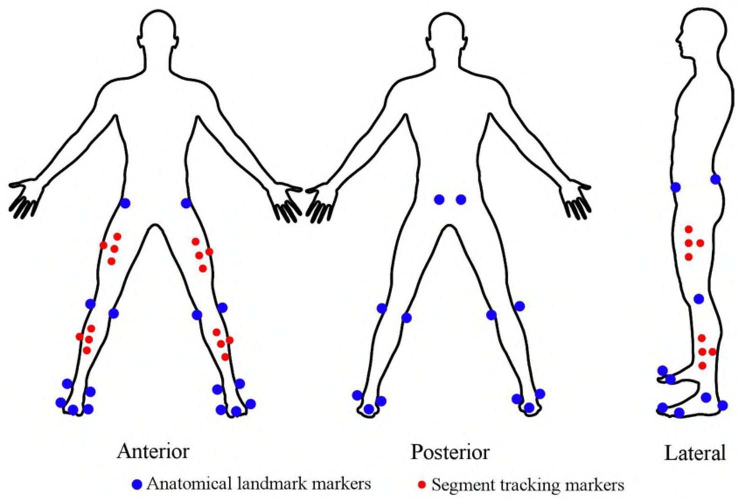

Fig 1. Lower body Plug-In-Gait model. Blue markers define the required anatomical landmarks, red markers are used for tracking segments.

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Fig 2. Lila™ Exogen™ compression shorts and calf sleeves with thigh and shank loading.

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velocity defined by 6 s shuttle efforts. Owing to the requirement of 180° changes of direction after each shuttle, running velocities achieved through the capture area were greater than the theoretical straight-line velocity of 3.3 $m.s^{-1}$. Analysis of pilot data showed mean ± SD velocities of 4.16 ± 0.36 $m.s^{-1}$ through the capture area. Such velocities are commonly described as "striding" or "running" in field based sports, but fall below the "high-intensity" classification, often defined as >5.4 $m.s^{-1}$ [43, 44]. The first trial was performed with body weight only (BW), and participants completed 2 min worth of 20 m shuttles with the 6 s pacing speed per shuttle. Captures were taken each time participants passed through the 10 m mark capture area during runs from the start point to the 20 m mark only. Captures were not performed on the return shuttles. This process yielded capture of 10 complete strides across the 2 min trial.

Participants performed three subsequent 2 min running trials in which they were allocated WR loading of 1%, 3%, and 5% of body weight in a randomised order. Each trial was interspersed with a 3 min rest period. The result of this protocol was 10 complete overground running strides per condition, per participant.

Data processing

Visual 3D software (C-motion, Rockville, MD, USA) was used to construct a four segment model (pelvis, thigh, shank, and foot) for each participant. Within each participant, the leg on which most complete strides were successfully captured was used for analysis. This approach maximised available data given that individual stride characteristics tended to allow one side to be captured more consistently within the bounds of the 6 m capture area (see S1 Table for the leg used for each participant). Runs in which several marker trajectories were lost or accurate model construction could not be satisfied were excluded from analysis. Out of a possible 560 runs per-joint, 510 were successfully reconstructed for the hip, 530 for the knee, and 521 for the ankle. For a record of excluded runs and the participants and runs to which these pertained, see S1 Table. For successfully reconstructed runs, marker trajectories were smoothed via a fourth order low-pass Butterworth filter with 10 Hz cut-off frequency, based on mean residual amplitudes [45]. Each run was trimmed to one complete stride cycle, which was defined as the period between two consecutive toe-off events on the same limb. Toe-off was defined by the initial rise in vertical displacement of the toe marker proceeding its lowest point at the end of the support phase [46, 47]. Time-continuous sagittal plane joint angles for the hip, knee, and ankle (°) were normalised to 100% of the stride cycle for further analysis. Positive and negative joint angles were defined relative to the positions of joints in upright standing. Positive joint angles indicate positions of hip flexion, knee flexion, and ankle dorsiflexion relative to standing, while negative joint angles indicate positions of hip extension, knee extension, and ankle plantarflexion relative to standing.

Data analysis

Running velocity was compared across different loading conditions using a one-way repeated measures ANOVA with Bonferroni correction applied to post-hoc pairwise comparisons. A significance level of $\alpha = 0.05$ was used.

Statistical parametric mapping t-test. Comparisons between continuous joint angle kinematic data in the BW condition and each loading condition were performed across the group, including participants of both sexes, to identify global effects of loading. Statistical parametric mapping (SPM) t-tests were used in each instance with $\alpha = 0.05$, as previously described [48, 49]. Kinematic data were estimated as functions using B-splines. A smoothing parameter of 0.01 was used in the fitting procedure. A t-statistic trajectory was created across the gait cycle and assessed in relation to a critical t-statistic, which was determined using a permutation test by randomly shuffling the labels of the curves and recalculating the maximum t-statistic using these new labels. The analysis was done using R (version 3.6.0) and code used can be accessed at https://github.com/ktrounson/WR-running/blob/master/FDA%20t-test.

Generalised additive model. Generalised additive models (GAMs) were fit to continuous joint angle data, with separate GAMs for each joint. In each case, data was modelled as a function of the percentage of the stride cycle. Cyclic cubic regression splines were used to generate basis functions for each condition and smoothing was achieved using the restricted maximum likelihood method. Cubic regression splines are more appropriate for functional data that represent repeated cycles of the same event [50]. The number of knots was increased until the maximum deviance explained by the model was reached.

For visualisation of joint kinematic trends and between-run variability on an individual basis, runs from each participant were treated as random effects. The random effects estimates were plotted as a function of condition within each participant. Female participants are labelled F1-F3 and male participants are labelled M1-M11. All GAM code is provided at https://github.com/ktrounson/WR-running/blob/master/GAMs.

Bivariate functional principal component analysis. Bivariate functional principal component analysis (*bf*PCA) applied to angle-angle kinematic data allows for the dominant modes of variation to be estimated. *bf*PCA was used to analyse concurrent hip-knee and knee-ankle kinematics using B-spline basis functions [51–53]. The smoothing parameter was selected using a generalised cross validation procedure and was set at 0.1 and 0.18 for the hip-knee and knee-ankle data, respectively. *bf*PCs were derived from the smoothed curves. Each *bf*PC was varimax rotated to assist with interpretation of results. The occurrence and magnitude of angle-angle variability was graphically represented by the first two *bf*PCs on individual plots containing the ensemble mean of curves along with two additional curves representing +/- 2SD of the *bf*PC scores for each *bf*PC. *bf*PCA was performed in R with code available at https://github.com/ktrounson/WR-running/blob/master/bfPCA.

Individual-based 2D plots were generated in which mean *bf*PC scores for each condition were mapped along the first two *bf*PCs for each joint pairing. Positive scores along a dimension indicate that, on average, runs within this condition resembled more closely the characteristics of the '+' curve, while negative scores indicate a closer resemblance to the '-' curve.

Results

Mean running velocities across participants in each condition are included in Table 1. A significant main effect of condition was evident ($F = 4.77$, $p = 0.003$). Post-hoc analysis showed slower running velocities in the 5% loading condition compared with all other conditions.

SPM t-test

Continuous ensemble means per-joint and per-condition with associated standard deviations are presented in Fig 3. Sections of significant difference between the BW condition and

Table 1. Mean ± SD running velocities in each condition with post-hoc pairwise comparisons.

Condition	Running velocity (m.s^{-1})	p-value vs. 1%	p-value vs. 3%	p-value vs. 5%
BW	4.25 ± 0.43	1	1	0.017
1%	4.25 ± 0.47		1	0.005
3%	4.25 ± 0.48			0.022
5%	4.18 ± 0.44			

BW, body weight; 1%, 1% of body weight WR loading; 3%, 3% of body weight WR loading; 5%, 5% of body weight WR loading.

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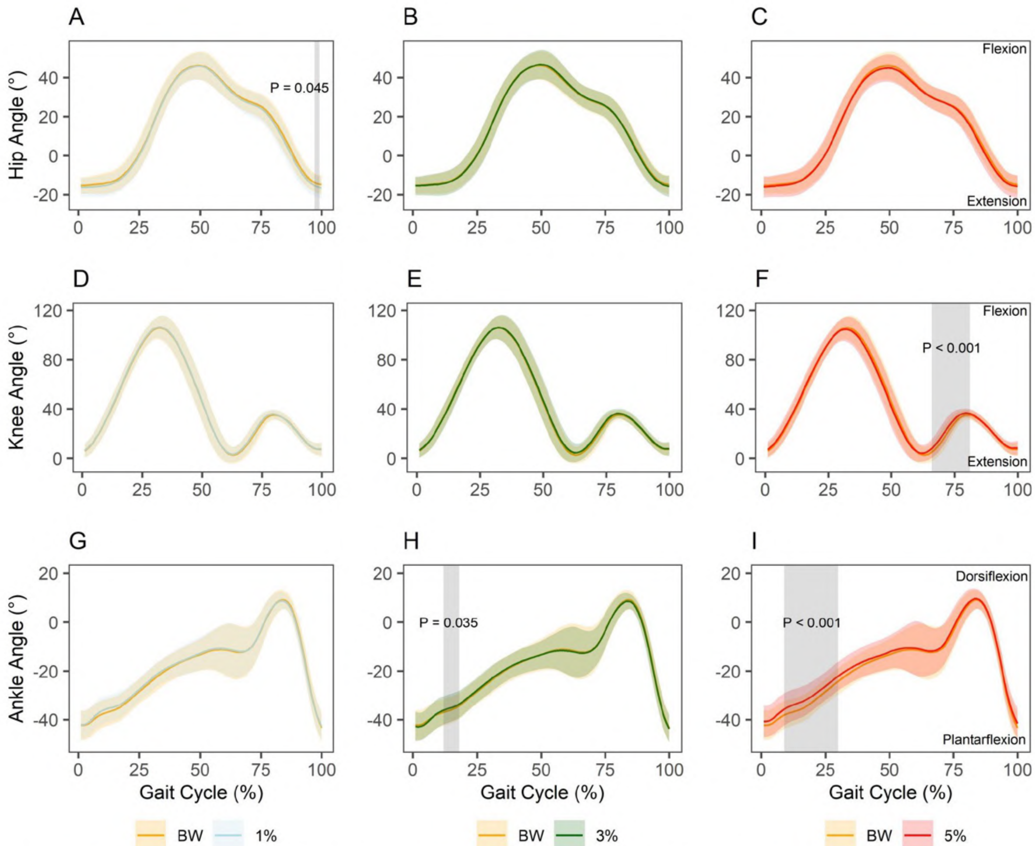

Fig 3. SPM t-test per-joint and per-condition versus BW. (A) Hip joint BW versus 1%. (B) Hip joint BW versus 3%. (C) Hip joint BW versus 5%. (D) Knee joint BW versus 1%. (E) Knee joint BW versus 3%. (F) Knee joint BW versus 5%. (G) Ankle joint BW versus 1%. (H) Ankle joint BW versus 3%. (I) Ankle joint BW versus 5%. Solid lines represent ensemble means and accompanying shaded regions represent ± 1 SD. Grey shaded regions indicate regions of significant difference between curve sets.

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each loading condition according to SPM t-tests are indicated. WR loading of 1% of body weight led to greater hip extension at 97–99% of the gait cycle (just prior to toe-off) compared with BW ($P = 0.045$). Loading of 3% of body weight resulted in less ankle plantarflexion from 12–18% of the gait cycle (during heel recovery) compared with BW ($P = 0.035$). Loading of 5% of body weight resulted in greater knee flexion from 66–81% of the gait cycle (during weight acceptance) ($P < 0.001$) and less ankle plantarflexion from 9–30% of the gait cycle (during heel recovery) compared with BW ($P < 0.001$). Pointwise t-statistics and the maximum critical value for a significance level of 0.05 for each set of curves are provided in S2 Table.

Table 2. Generalised additive model summary statistics per-joint.

		Parametric coefficients				Smooth terms		
Joint	**Condition**	**Estimate**	**Standard error**	**t-value**	**Pr(>|t|)**	**EDF**	**F**	**p-value**
Hip	**BW (intercept)**	14.16	1.35	10.5	> 0.001	12.96	22666.3	> 0.001
	1%	-0.65	0.06	-10.99	> 0.001	3.8	4.94	> 0.001
	3%	-0.12	0.06	-2.05	0.04	4.51	3.64	> 0.001
	5%	-0.71	0.06	-11.76	> 0.001	7.62	7.12	> 0.001
Knee	**BW (intercept)**	43.21	1.15	37.65	> 0.001	8	32137.8	> 0.001
	1%	0.55	0.1	5.25	> 0.001	4.05	1.47	0.009
	3%	0.71	0.1	6.86	> 0.001	3.54	7.42	> 0.001
	5%	0.15	0.1	1.48	0.14	7.29	52.18	> 0.001
Ankle	**BW (intercept)**	-18.5	1.06	-17.48	> 0.001	20.85	6141	> 0.001
	1%	0.33	0.07	4.95	> 0.001	5.85	2.6	> 0.001
	3%	-0.15	0.07	-2.18	0.03	3.91	1.77	> 0.001
	5%	1.31	0.07	19.49	> 0.001	5.55	5.06	> 0.001

EDF, estimated degrees of freedom; BW, body weight; 1%, 1% of body weight WR loading; 3%, 3% of body weight WR loading; 5%, 5% of body weight WR loading.

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GAMs

The summary statistics of each joint GAM are shown in Table 2. For BW, the estimate indicates the mean joint angle across the stride cycle. For loading conditions, estimates indicate the difference in mean joint angle across the stride cycle versus BW. Estimated degrees of freedom reflect the number of basis functions used to generate the smooths and therefore a higher number of estimated degrees of freedom suggests more variable data. For loading conditions, estimated degrees of freedom are in addition to those listed for BW.

The GAM random effects estimates per-run are shown in Fig 4. Random effects estimates reflect the prevailing flexion-extension bias throughout the stride cycle relative to the group mean. The distribution of random effects estimates appeared to be more strongly driven by the participant in question than within-participant responses to WR loading. However, individual-level responses of note include instances in which loading increased between-run variability, such as at the ankle in the 5% condition for F1, the knee in the 5% condition for M1, the knee in the 1% condition for M2, the knee in all loading conditions for M3, the hip and ankle in the 3% condition for F2, and the hip in the 5% condition for M7. Conversely, decreased between-run variability was evident at the ankle in the 3% condition for M1, the ankle in the 3% and 5% conditions for M2, the hip in the 5% condition for M5, the ankle in the 5% condition for F2 and M6, and the ankle in the 1% condition for F3. Shifts in the prevailing random effects estimates on the basis of loading appeared evident at the ankle in the 1% and 3% conditions for M2, the hip in the 3% condition for M3 and F2, the ankle in the 5% condition for M6, the hip in the 3% and 5% conditions for M7, the hip in the 1% condition for F3, and the hip in the 1% and 3% conditions for M11.

*bf*PCA

For hip-knee joint coupling, *bf*PC1 explained 41.1% of the variability in the group data (Fig 5). Positive scorers on *bf*PC1 exhibited less knee flexion during the swing phase, while negative scorers exhibited greater knee flexion. *bf*PC2 explained 23.3% of the variability in the group data. Positive scorers on *bf*PC2 exhibited greater hip flexion during the swing phase, while negative scorers exhibited less hip flexion and hip flexion was delayed compared with positive scorers. For knee-ankle joint coupling, *bf*PC1 explained 45.6% of the variability in the group

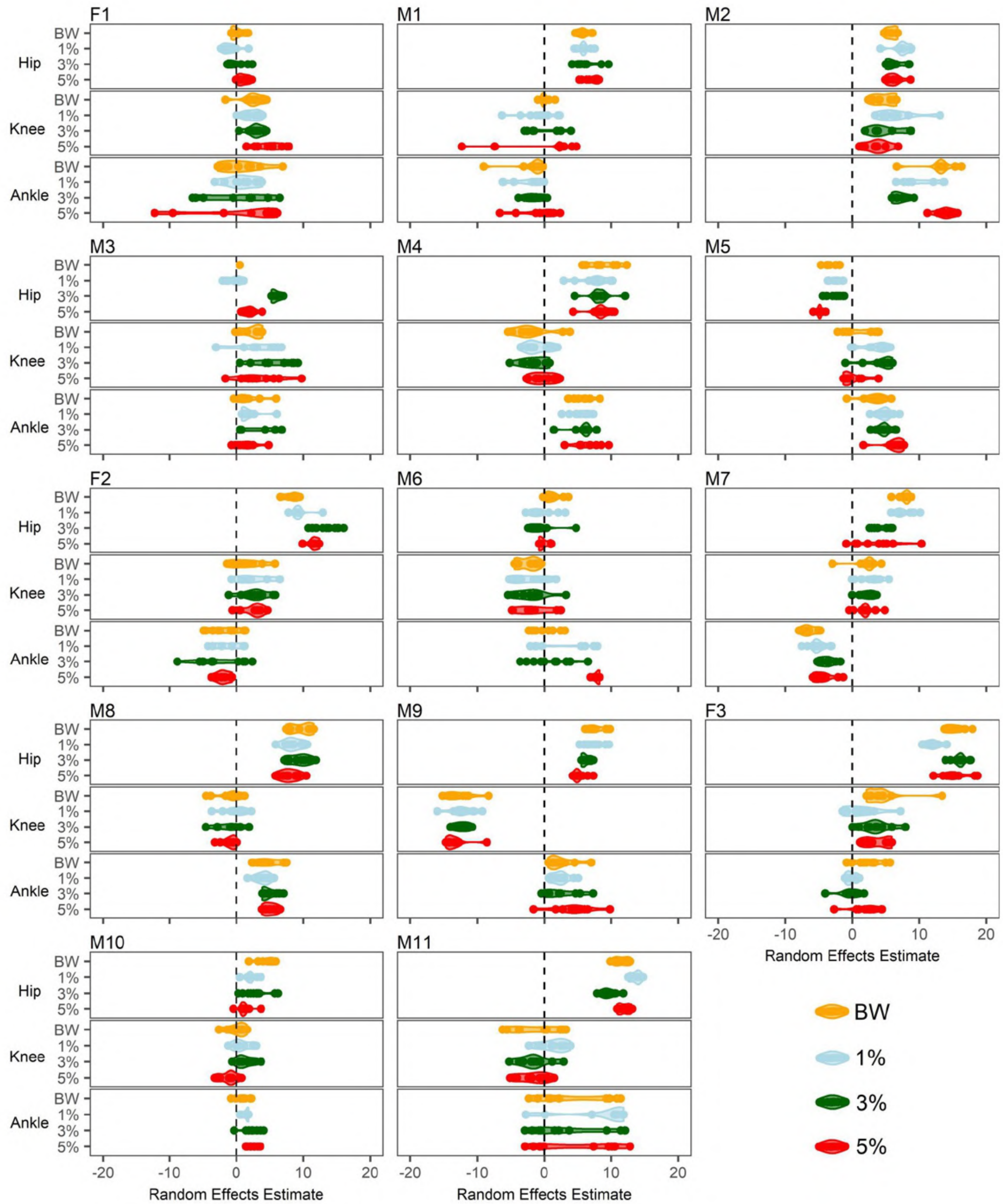
F1
M1
M2
M3
M4
M5
F2
M6
M7
M8
M9
F3
M10
M11
Hip
Knee
Ankle
BW
1%
3%
5%
-20
-10
0
10
20
Random Effects Estimate

Fig 4. GAM random effects estimates per-run, per-individual. Each major panel relates to a given participant, as denoted by labels. Joints are separated by the three minor panels within each participant plot. Conditions are expressed as categories within each joint and associated colours have been included for clarity. Positive estimates indicate greater hip flexion, knee flexion, and ankle dorsiflexion relative to the group mean. Negative estimates indicate greater hip extension, knee extension, and ankle plantarflexion. Thicker regions of coloured portions reflect a greater concentration of runs with similar random effects estimates.

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data. Positive scorers exhibited less knee flexion during the swing phase and negative scorers exhibited greater knee flexion. *bf*PC2 explained 16.8% of the variability in the group data. Positive scorers on *bf*PC2 exhibited less ankle plantarflexion, particularly at touchdown, while negative scorers exhibited greater ankle plantarflexion during late swing and touchdown.

Mean individual *bf*PC scores along both *bf*PCs for hip-knee and knee-ankle joint pairs across runs in each condition are shown in Fig 6. Participants appeared to have mostly distinct joint coupling profiles and there was some impact of WR loading within-individuals. There was generally agreement between observations of condition-based shifts in random effects estimates from GAM analysis and differences in mean *bf*PC scores, including in the knee-ankle joint couple in the 3% condition for M2, the hip-knee joint couple in the 3% condition for M3 and F2, the knee-ankle joint couple in the 5% condition for M6, the hip-knee joint couple in the 3% and 5% conditions for M7, and the hip-knee joint couple in the 1% condition for F3 and M11. Additional condition-based shifts apparent from *bf*PCs included the hip-knee joint couple in the 1% condition in M2, the hip-knee joint couple in the 5% condition for M3, M6, M8, and M10, and the knee-ankle joint couple in the 1% condition for M11. Shifts that were identified from GAM analysis but that appeared to be minimal based on *bf*PC plots included the knee-ankle joint couple in the 1% condition for M3 and the hip-knee joint couple in the 3% condition for M11.

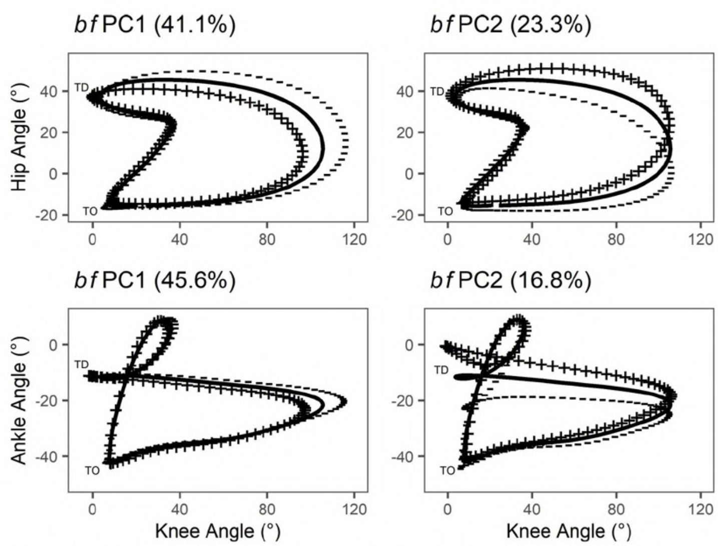

Fig 5. *bf*PCA of hip-knee and knee-ankle joint couples throughout stride cycle. First two bfPCs from hip-knee and knee-ankle *bf*PCA with the percentage of group variability explained. Solid line represents the mean angle-angle curve. '+' line represents positive scorers +2SD from the mean function. '-' line represents negative scorers -2SD from the mean function.

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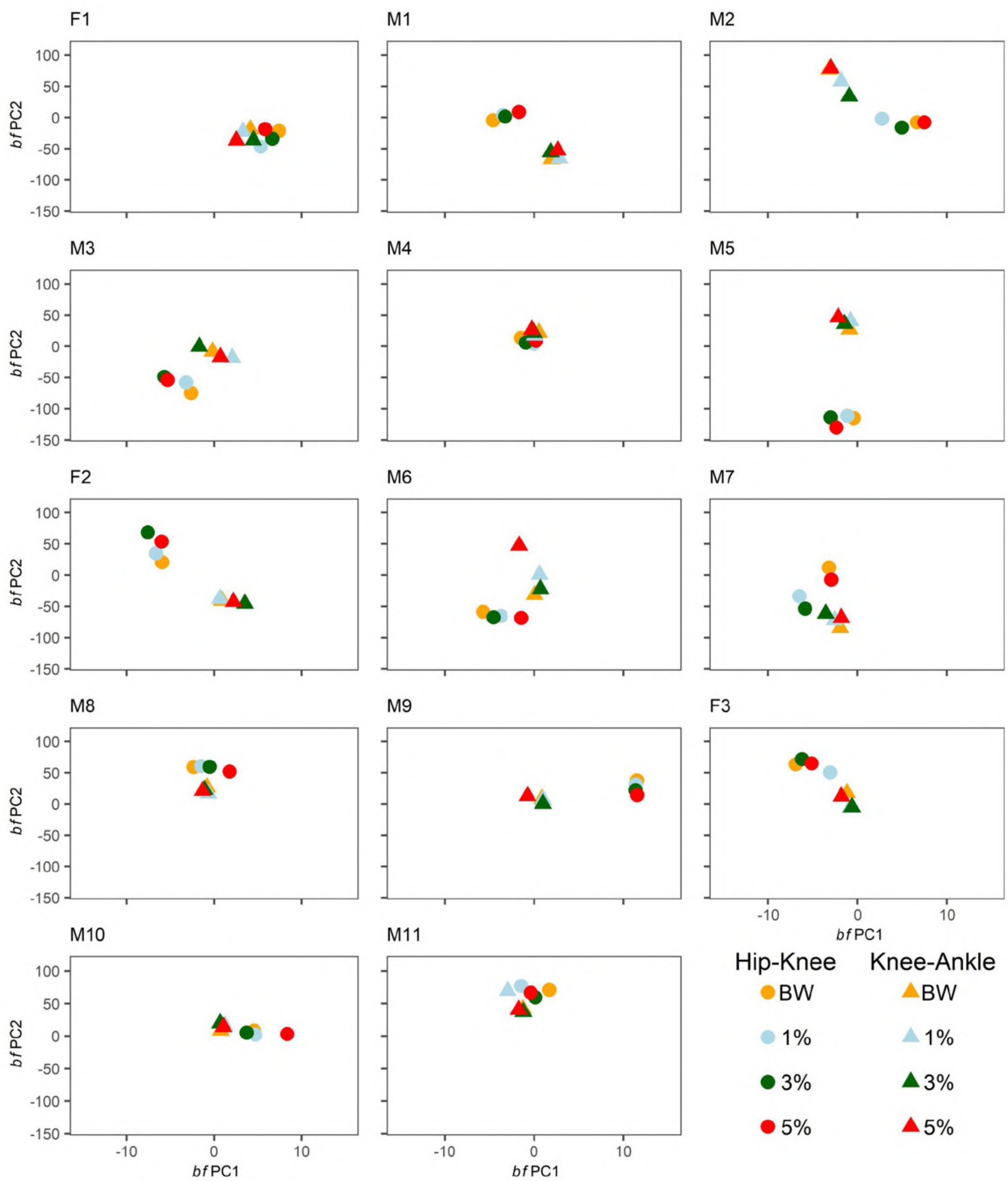
F1
M1
M2
M3
M4
M5
F2
M6
M7
M8
M9
F3
M10
M11
bf PC2
bf PC1
Hip-Knee
Knee-Ankle
BW
1%
3%
5%

Fig 6. Individual mean hip-knee and knee-ankle *bf*PC1 and *bf*PC2 scores per-condition. Each panel relates to a given participant, as denoted by labels. Mean hip-knee *bf*PC scores across runs within a condition are denoted by circle labels. Mean knee-ankle *bf*PC scores across runs within a condition are denoted by triangle labels. Separate conditions are indicated by distinct colours.

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Discussion

This study examined the effects of lower limb WR loading on coordination tendencies during sub-maximal overground running. Specifically, the study sought to describe the effects of various WR magnitudes (1%, 3%, and 5% of body weight) on lower limb sagittal plane joint kinematics at a group- and individual-level, both in terms of continuous gait cycle kinematics and between-run movement variability. The main findings at a group-level were that 3% and 5% loading decreased ankle plantarflexion during heel recovery, while 5% loading also increased knee flexion during weight acceptance, compared with BW running. In terms of joint coupling, 5% loading brought about the largest changes in coordination at the hip-knee joint pair. At an individual-level, six of the fourteen participants clearly exhibited increased between-run joint angle variability at one or more joints in one or more loading conditions compared with BW.

Running velocity was slower in the 5% condition compared with all other conditions, however, the magnitude of this difference was minimal at just 0.07 $m.s^{-1}$. All participants maintained speeds sufficient to successfully complete all shuttles within the allotted time frames in all conditions.

In terms of kinematics at the group-level, slight decreases in ankle plantarflexion during heel recovery occurred with 3% loading compared with BW running. The 5% loading condition led to more substantial decreases in ankle plantarflexion during heel recovery, as well as increased knee flexion during weight acceptance. The exhibition of greater knee flexion was likely a mechanism to mitigate increased peak ground reaction force arising from the greater system load [54, 55]. Explanations for less plantarflexion during heel recovery are more speculative. One possibility is that participants subconsciously attempted to offset the greater moment of inertia at the thigh by dorsiflexing the ankle to create a mechanical advantage during swing leg recovery [56, 57]. Alternatively, or perhaps in addition, heavier loading likely led to increased co-contraction of muscles around the ankle joint during stance for maintenance of stiffness and stability [55, 58]. Such alterations in motor unit recruitment and temporal sequencing of lower leg muscles may constrain the action of this joint during the subsequent propulsion and swing phase, with the joint returning to a relatively more neutral position more readily [59, 60]. The impact of coordination dynamics should also be considered. Individuals performing novel motor tasks often exhibit freezing of distal biomechanical degrees of freedom to reduce coordinative complexity [61–63]. To the extent that running with an extra 5% of body weight on the lower limbs was perceived as a novel task, there may have been a tendency for participants to return to a more neutral ankle position following toe-off. Given these factors, 5% loading, and to a lesser extent 3% loading, may be excessive as a means of promoting movement variability for some individuals in the first instance. The group-level changes suggest a degree of convergence toward a common adaptation strategy and appear consistent with movement options being limited by task novelty and/or the need to manage high loads. Coaches should take this into consideration if prescribing WR for multiple athletes without individualisation [64].

Despite group-level trends, individual responses varied. The practical utility of WR for inducing movement variability is therefore likely to also be individual-dependent. Coaches should appreciate the range of individual responses and use the present findings as signposts to guide individual WR prescription in the field.

Participants F1, M1, M2, M3, F2, and M7 all exhibited increased between-run variability in mean angles at one or more joints in one or more loading conditions compared with BW. These high variability instances suggest that there was no readily accessible adaptive mode to satisfy the task goal in the presence of WR and instead a period of search and refinement of individuals' preferred coordinative structures was required [65, 66]. WR in this context therefore provides an opportunity to explore movement system degeneracy. For these individuals, exposure to WR over a training period may facilitate development of movement adaptability and allow running performance to be more readily maintained when perturbations arise in competition [10, 67]. The propensity for individuals to exhibit greater variability at one loading condition over another is largely a function of intrinsic behavioural dynamics, which dictate system tendencies such as attractor state stability and behavioural meta-stability [68, 69].

A definitive reduction in between-run variability was present in participants F2 and M6 at the ankle joint in the 5% loading condition. This may align with the proposed group-level hypothesis of distal joint freezing in this condition. While established literature tends to define freezing degrees of freedom as restricted movement of a joint within-trials, low between-trial variability is also indicative of constrained movement [20, 70]. Among these individuals, the perturbation of 5% loading may have been managed by increasing co-contractions and stiffening muscles of the lower limbs, as occurs in the early stages of skill acquisition [61]. Interestingly, this can be considered an adaptive strategy in itself, particularly since performance of shuttle runs was successfully maintained. This therefore raises the need to clarify the benefit of perturbations that encourage movement variability during training versus those that limit movement variability. Findings from balance beam walking with different perturbation magnitudes demonstrate that learning under conditions in which sacral movement variability is maximised leads to superior learning and subsequent task performance post-training [71]. Substantially increasing the level of perturbation through an error augmenting device decreases movement variability in line with individuals attempting to maintain control of movement, and has suboptimal outcomes for post-training performance [71]. Separately, Chmielewski *et al.* [60] argue that increased co-contractions as a means of adapting to an ACL rupture reflect a suboptimal compensation pattern wherein the capacity to dynamically stabilise the injured knee without compromising knee motion has not yet been developed. Taken together, these findings highlight that large magnitude perturbations may be adapted to by reducing movement variability, however, skill acquisition is not facilitated under these conditions. Reduced movement variability affords fewer opportunities for internal models of limb dynamics to be updated, which may limit the extent to which adaptability is trained [72].

Among high performing field-based athletes, some individuals are likely to already have well developed functional movement adaptability [11, 12]. This is typified by an appropriate mix of movement pattern flexibility and stability, such that coordination can be readily adjusted in response to a perturbation and movement variability levels remain similar to those at baseline [10, 73]. Potential exemplars of this in the present study include participant M10 in all loading conditions and participant M7 in the 3% loading condition.

Participants M4 and M9 exhibited no discernable joint kinematic changes at any loading magnitude. Between-run variability also appeared consistent across loading. For these individuals, loading even up to 5% of body weight may not have required additional exploitation of movement system degeneracy to satisfy the task goal [74]. As part of their intrinsic behavioural dynamics, these individuals likely defer to highly stable movement attractor states in the presence of manageable perturbations [65, 75]. Practically, WR may not be appropriate to challenge running coordination among such individuals, as loading beyond 5% of body weight on the lower limbs presents logistical difficulties due to load placement space limitations.

Lastly, it is interesting to note that participants M2 and M11 appeared to demonstrate multi-stability about the ankle joint. There appeared to be two dominant kinematic modes expressed with apparent condition dependence in M2 but not in M11. Coaches should appreciate that athletes may exhibit multi-stability, wherein two or more patterns of coordination are stable [68].

A limitation of the present study is that only sagittal plane kinematics were considered. Consequential alterations to kinematics may have also occurred in the transverse and frontal planes, or in trunk or upper body segments. In terms of the WR, an exactly equal distribution of load between the anterior and posterior segment surfaces could not always be guaranteed. In these instances, one surface of each segment experienced 50 g more loading, which although minimal, may have impacted ensuing running kinematics. In relation to data processing, it is important to acknowledge that although the initial rise in vertical displacement of the toe marker has previously been used to define toe-off during running actions [46, 47, 76], validation of this detection method against force plate measures under the specific running velocities and floor surface conditions of the present study has not been performed. Lastly, despite the 3 min rest period allowed between running trials, residual after-effects following heavier loading conditions could have briefly impacted on the kinematics observed during lighter conditions [77]. When SPM t-tests were repeated with participants separated on the basis of having completed the 1% condition immediately following the 5% condition as part of their randomisation, it was evident that the group-level differences in hip extension between the 1% condition and BW were driven by these participants (S1 Fig). A larger sample size would provide clarity on this point by enabling direct statistical comparisons between participants who experienced the 1% condition immediately following the 5% condition, and those that did not. If this type of loading contrast was an effectual factor, fidelity could be improved by allowing participants to rest for longer or briefly run without loading in between trials to "re-establish" an unloaded baseline.

Future research should specifically consider the effects of unloaded running immediately following a period of loading to clarify the propensity for acute coordinative changes to be retained following the removal of perturbation. Investigation into the impact of asymmetrical WR loading on coordination would also be worthwhile given the challenge to the movement system that such an intervention would pose. As understanding of the effects of WR loading develops, researchers and/or coaches should consider situating tasks such as loaded running in a representative, field-based environment. WR coupled with the inherent movement variability induced by dynamic constraints and affordances in this environment would present a further, more contextual, challenge to coordination [78].

Conclusions

Exposure to WR of 5% of body weight increased knee flexion during weight acceptance and decreased ankle plantarflexion during heel recovery at the group-level. This appeared to be due to the high load and novelty of this condition. Among individuals that reflected group-level trends and exhibited decreased between-run variability at one or more joints, 5% loading may be an excessive perturbation, as exploration of alternate movement states is limited. Several participants exhibited increased between-run joint angle variability in one or more loading conditions compared with BW, suggesting exploration and refinement of coordinative structures under these conditions. The loading magnitudes at which these increases were elicited, however, varied between individuals. WR therefore appears to show utility for the purpose of perturbing coordination to encourage movement variability among certain individuals, though the loading magnitudes used should be determined on a case-by-case basis.

Supporting information

S1 Table. List of legs analysed and joint angles unable to be reconstructed for analysis. Joint angle data that could not be reconstructed is highlighted in red.
(DOCX)

S2 Table. Pointwise t-statistics and maximum critical values for SPM t-tests.
(DOCX)

S1 Fig. Hip joint SPM t-test BW versus 1% separated based on condition order. (A) Hip joint BW versus 1% for participants in which 1% condition did not immediately proceed 5% condition. (B) Hip joint BW versus 1% for participants in which 1% condition immediately proceeded 5% condition. Solid lines represent ensemble means and accompanying shaded regions represent ± 1 SD. Grey shaded regions indicate regions of significant difference between curve sets.
(TIF)

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3.1 Abstract

Field-based sports require athletes to run sub-maximally over significant distances, often while contending with dynamic perturbations to preferred coordination patterns. The ability to adapt movement to maintain performance under such perturbations appears to be trainable through exposure to task variability, which encourages movement variability. The aim of the present study was to investigate the extent to which various wearable resistance loading magnitudes alter coordination and induce movement variability during running. To investigate this, 14 participants (three female and 11 male) performed 10 sub-maximal velocity shuttle runs with either no weight, 1%, 3%, or 5% of body weight attached to the lower limbs. Sagittal plane lower limb joint kinematics from one complete stride cycle in each run were assessed using functional data analysis techniques, both across the participant group and within-individuals. At the group-level, decreases in ankle plantarflexion following toe-off were evident in the 3% and 5% conditions, while increased knee flexion occurred during weight acceptance in the 5% condition compared with unloaded running. At the individual-level, between-run joint angle profiles varied, with six participants exhibiting increased joint angle variability in one or more loading conditions compared with unloaded running. Loading of 5% decreased between-run ankle joint variability among two individuals, likely in accordance with the need to manage increased system load or the novelty of the task. In terms of joint coordination, the most considerable alterations to coordination occurred in the 5% loading condition at the hip-knee joint pair, however, only a minority of participants exhibited this tendency. Coaches should prescribe wearable resistance individually to perturb preferred coordination patterns and encourage movement variability without loading to the extent that movement options become limited.

3.2 Introduction

Across many field-based sports, athletes must be capable of running long distances throughout a match (Varley et al. 2014; Dawson et al. 2004; Suarez-Arrones et al. 2012). Depending on the sport, total running distance can range from an average of 6 km in rugby league to 12 km in Australian Rules football (Varley et al. 2014). In Australian Rules football, soccer, rugby league, and rugby sevens, most of the distance covered during match play can be classified as “low-intensity activity”, i.e., occurring at velocities <5.4 m.s^{-1}

(Varley et al. 2014; Suarez-Arrones et al. 2012). While high-intensity efforts are often associated with significant match events, adequate sub-maximal running capabilities are also important for effective opponent tracking and retention of team formations during different phases of play throughout a match (Andrzejewski et al. 2016). As such, training aimed at developing sub-maximal overground running performance is evidently worthwhile.

Development of sub-maximal running performance for field-based athletes is a multifactorial proposition and requires training of aerobic capacity, biomechanical factors for superior economy, and muscular strength (Moore 2016; Morgan et al. 1989; Conley and Krahenbuhl 1980; Folland et al. 2017). Coaches should address these factors in training prescription and, in addition, athletes' ability to adapt their running coordination patterns in accordance with the dynamic constraints of the sport (Komar et al. 2015; Barris et al. 2014). The capacity to exhibit "adaptability" in this sense allows for greater maintenance of performance in varied contexts and is a hallmark of higher performing athletes in many sports (Schorer et al. 2007; Barris et al. 2014; Chow et al. 2006a; van Emmerik et al. 2016). In field-based sport, organismic constraints in the form of local metabolite accumulation from intermittent anaerobic efforts (Bishop 2012; Morel et al. 2015), muscle damage arising from high force eccentric contractions during decelerations (Thompson et al. 1999), and muscular contusion from compressive force impacts (Gabbe et al. 2002), all present scenarios in which there is a challenge to an athlete's preferred running coordinative structure, which must be adapted to.

Critically, the implementation of a training intervention aimed at encouraging movement variability in diving (Barris et al. 2014) suggests that the capacity for athletes to harness movement system degeneracy to maintain a performance outcome is trainable. Alteration of a single task constraint – in this case heavily penalising balking – increased repetition-to-repetition variability in the relationship between joint angles among elite female springboard divers and this correlated with superior dive performance (Barris et al. 2014). The notion of developing execution variability is further supported by nonlinear pedagogical training interventions in youth tennis (Lee et al. 2014). Individuals exposed to greater task variability during training displayed a greater number of unique movement clusters, indicating the presence of degeneracy, during performance tasks. Exposure to task variability drives exploration of alternate movement strategies, or movement variability, as movement is adjusted to satisfy novel task demands (Chow et al. 2011). Training in this way affords individuals the ability to adapt movement to maintain task performance under the varied constraints occurring in the dynamic sporting environment (Lee et al. 2014; Chow et al. 2007; Barris et al. 2014).

In the context of sub-maximal running kinematics, the effects of deliberately induced task variability through perturbation have been explored in research using elastic tubes attached from the hips to the ankles (Haudum et al. 2014, 2012a; Haudum et al. 2012b). This intervention increases joint kinematic variability acutely, after which there is relatively rapid stabilisation around a slightly shifted coordinative structure (Haudum et al. 2012b; Haudum et al. 2014). Although no post-training running test under novel conditions was undertaken, the performance benefits associated with exposure to constraints, which encourage movement variability in this way, are widely reported (Hernandez-Davo et al. 2014; García-Herrero et al. 2016; Savelsbergh et al. 2010; Schöllhorn et al. 2010b; Harbourne and Stergiou 2009).

It is also worth noting that analyses of kinematic variability induced by constraint implementation to date have typically focussed on group-level changes (Haudum et al. 2014; Apps et al. 2017; Frank et al. 2013). Increasingly, there is support for individual-level consideration given that intrinsic behavioural dynamics and baseline kinematic characteristics alter the extent to which a particular constraint is experienced as a perturbation to the system (Kostrubiec et al. 2012; Schöllhorn et al. 2002; Schöllhorn and Bauer 1998). Kinematic changes may vary markedly between individuals, which may not be clear when considering generalised responses, yet is important in a practical setting (Apps et al. 2014; Walker et al. 2019; Alfonso and Menayo 2019).

Lightweight wearable resistance (WR) may be a useful training tool for encouraging exploration of movement system degeneracy through movement variability. WR involves attachment of small weights to particular body segments, such as the trunk, arms, thighs, and shanks (Macadam et al. 2019a). To date, research has considered WR in its capacity as a movement specific overload stimulus (Simperingham and Cronin 2014; Simperingham et al. 2016), however, WR also presents a perturbation to coordination, which may induce movement variability. WR application alters segment inertial properties and as such can be considered an organismic constraint (Field et al. 2019; Martin and Cavanagh 1990).

Exposure to WR may ultimately be a useful stimulus for developing adaptable movement behaviours among athletes in preparation for changing organismic constraints faced during match play. This study aimed to describe the extent to which different acute lower limb WR loadings (1%, 3%, and 5% of body weight) alter coordination and induce movement variability during sub-maximal overground running. To address this aim, analytical methods, which go beyond conventional gait analysis techniques that focus on peak or mean values from discrete events within the gait cycle, were used. These methods capture to a greater extent the nonlinear, time-dependent, and inter-joint changes brought about by WR. By considering both group- and individual-level responses, findings will provide context for coaches seeking to promote movement variability without imposing an excessive perturbation that limits movement options.

3.3 Materials and methods

3.3.1 Participants

Fourteen participants (three female and 11 male; mean ± SD: age 28.3 ± 4.4 years; height: 179.9 ± 7.6 cm; body mass: 76.8 ± 6.1 kg) volunteered to participate in this study. Participants were included on the basis that they were currently undertaking, or had recent previous experience (past year), in structured field-based sport competition. Participants in the study had no prior experience with WR. All participants provided written informed consent and were free from injury at the time of testing. All procedures used in this study complied with the criteria of the declaration of Helsinki and the ethical approval granted by the Victoria University Human Research Ethics Committee.

3.3.2 Procedure

3.3.2.1 Data collection apparatus

A 10-camera VICON motion analysis system (T-40 series, Vicon Nexus v2, Oxford, UK) sampling at 250 Hz was used for collection of kinematic data. A total of thirty-six reflective markers with 14 mm diameter were attached to lower body landmarks on the pelvis, thighs, shanks, and feet according to the Plug-In-Gait model (Plug-In-Gait Marker Set, Vicon Peak, Oxford, UK) (Fig 3.1).

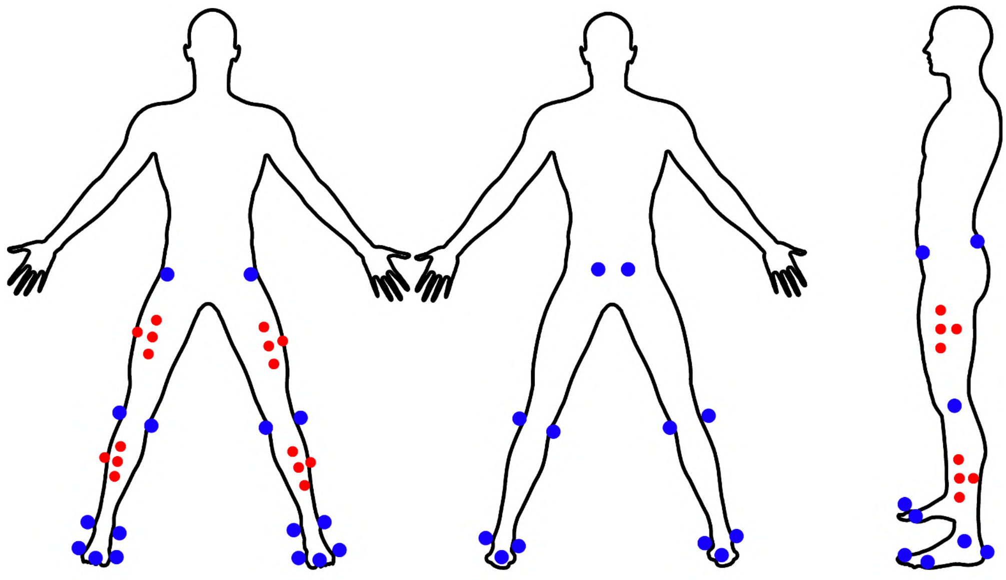

Fig 3.1 Lower body Plug-In-Gait model. Blue markers define the required anatomical landmarks, red markers are used for tracking segments.

3.3.2.2 Wearable resistance

Throughout testing, participants wore Lila™ Exogen™ (Sportboleh Sdh Bhd, Kuala Lumpur, Malaysia) compression shorts and calf sleeves. During WR exposure trials, a combination of 50, 100, and 200 g fusiform shaped loads (with Velcro backing) totalling the required proportion of participants' body weights were attached to the compression garments (Fig 3.2). Loads were distributed in a 2:1 thigh:shank ratio about the centre of mass of each segment (Macadam et al. 2017c). The required loads were added in an alternating fashion between the anterior and posterior surfaces, and between a proximal-dominant and distal-dominant orientation, in order to avoid a large shift in the centre of mass of each segment.

Fig 3.2 Lila™ Exogen™ compression shorts and calf sleeves with thigh and shank loading.

3.3.2.3 Experimental setup

Testing was undertaken on a 20 m section of the Biomechanics Laboratory at Victoria University. Motion analysis cameras were arranged around the 10 m mark of the 20 m section and the approximate capture volume was 6.0 m long, 2.5 m high, and 3.0 m, wide.

3.3.2.4 Data collection

Following application of compression garments and attachment of reflective markers, participants undertook an initial warm-up in which they ran back and forth along the 20 m section in a "shuttle" fashion for 2 min. Running velocity was dictated through the use of an audible metronome, which counted each second from 1-9, before repeating for every subsequent shuttle. Participants underwent a 2 min rest period following the first warm-up run before performing a second warm-up run for 1 min at an increased velocity defined by 6 s shuttle efforts. Owing to the requirement of 180^{o} changes of direction after each shuttle, running velocities achieved through the capture area were greater than the theoretical straight-line velocity of 3.3 m.s^{-1}. Analysis of pilot data showed mean ± SD velocities of

4.16 ± 0.36 $m.s^{-1}$ through the capture area. Such velocities are commonly described as "striding" or "running" in field based sports, but fall below the "high-intensity" classification, often defined as >5.4 $m.s^{-1}$ (Suárez-Arrones et al. 2012; Carling et al. 2012). The first trial was performed with body weight only (BW), and participants completed 2 min worth of 20 m shuttles with the 6 s pacing speed per shuttle. Captures were taken each time participants passed through the 10 m mark capture area during runs from the start point to the 20 m mark only. Captures were not performed on the return shuttles. This process yielded capture of 10 complete strides across the 2 min trial.

Participants performed three subsequent 2 min running trials in which they were allocated WR loading of 1%, 3%, and 5% of body weight in a randomised order. Each trial was interspersed with a 3 min rest period. The result of this protocol was 10 complete overground running strides per condition, per participant.

3.3.3 Data processing

Visual 3D software (C-motion, Rockville, MD, USA) was used to construct a four segment model (pelvis, thigh, shank, and foot) for each participant. Within each participant, the leg on which most complete strides were successfully captured was used for analysis. This approach maximised available data given that individual stride characteristics tended to allow one side to be captured more consistently within the bounds of the 6 m capture area (see Appendix Table 1.1 for the leg used for each participant). Runs in which several marker trajectories were lost or accurate model construction could not be satisfied were excluded from analysis. Out of a possible 560 runs per-joint, 510 were successfully reconstructed for the hip, 530 for the knee, and 521 for the ankle. For a record of excluded runs and the participants and runs to which these pertained, see Appendix Table 1.1. For successfully reconstructed runs, marker trajectories were smoothed via a fourth order low-pass Butterworth filter with 10 Hz cut-off frequency, based on mean residual amplitudes (Winter 2009). Each run was trimmed to one complete stride cycle, which was defined as the period between two consecutive toe-off events on the same limb. Toe-off was defined by the initial rise in vertical displacement of the toe marker proceeding its lowest point at the end of the support phase (Schache et al. 2001; Nagahara and Zushi 2013). Time-continuous sagittal plane joint angles for the hip, knee, and ankle (°) were normalised to 100% of the stride cycle for further analysis. Positive and negative joint angles were defined relative to the positions of joints in upright standing. Positive joint angles indicate positions of hip flexion, knee flexion, and ankle dorsiflexion relative to standing, while negative joint angles indicate positions of hip extension, knee extension, and ankle plantarflexion relative to standing.

3.3.4 Data analysis

Running velocity was compared across different loading conditions using a one-way repeated measures ANOVA with Bonferroni correction applied to post-hoc pairwise comparisons. A significance level of $\alpha = 0.05$ was used.

3.3.4.1 Statistical parametric mapping t-test

Comparisons between continuous joint angle kinematic data in the BW condition and each loading condition were performed across the group, including participants of both sexes, to identify global effects of loading. Statistical parametric mapping (SPM) t-tests were used in each instance with $\alpha = 0.05$, as previously described (Warmenhoven et al. 2018; Ramsay et al. 2009). Kinematic data were estimated as functions using B-splines. A smoothing parameter of 0.01 was used in the fitting procedure. A t-statistic trajectory was created across the gait cycle and assessed in relation to a critical t-statistic, which was determined using a permutation test by randomly shuffling the labels of the curves and recalculating the maximum t-statistic using these new labels. The analysis was done using R (version 3.6.0) and code used can be accessed at https://github.com/ktrounson/WR-running/blob/master/FDA%20t-test.

3.3.4.2 Generalised additive model

Generalised additive models (GAMs) were fit to continuous joint angle data, with separate GAMs for each joint. In each case, data was modelled as a function of the percentage of the stride cycle. Cyclic cubic regression splines were used to generate basis functions for each condition and smoothing was achieved using the restricted maximum likelihood method. Cubic regression splines are more appropriate for functional data that represent repeated cycles of the same event (Wood et al. 2015). The number of knots was increased until the maximum deviance explained by the model was reached.

For visualisation of joint kinematic trends and between-run variability on an individual basis, runs from each participant were treated as random effects. The random effects estimates were plotted as a function of condition within each participant. Female participants are labelled F1-F3 and male participants are labelled M1-M11. All GAM code is provided at https://github.com/ktrounson/WR-running/blob/master/GAMs.

3.3.4.3 Bivariate functional principal component analysis

Bivariate functional principal component analysis (*bf*PCA) applied to angle-angle kinematic data allows for the dominant modes of variation to be estimated. *bf*PCA was used to analyse concurrent hip-knee and knee-ankle kinematics using B-spline basis functions (Warmenhoven et al. 2019; Ramsay and Silverman 2005; Harrison et al. 2007). The smoothing parameter was selected using a generalised cross validation procedure and was set at 0.1 and 0.18 for the hip-knee and knee-ankle data, respectively. *bf*PCs were derived from the smoothed curves. Each *bf*PC was varimax rotated to assist with interpretation of results. The occurrence and magnitude of angle-angle variability was graphically represented by the first two *bf*PCs on individual plots containing the ensemble mean of curves along with two additional curves representing ± 2SD of the *bf*PC scores for each *bf*PC. *bf*PCA was performed in R with code available at https://github.com/ktrounson/WR-running/blob/master/bfPCA.

Individual-based 2D plots were generated in which mean *bf*PC scores for each condition were mapped along the first two *bf*PCs for each joint pairing. Positive scores along a dimension indicate that, on average, runs within this condition resembled more closely the characteristics of the '+' curve, while negative scores indicate a closer resemblance to the '-' curve.

3.4 Results

Mean running velocities across participants in each condition are included in Table 3.1. A significant main effect of condition was evident ($F = 4.77$, $p = 0.003$). Post-hoc analysis showed slower running velocities in the 5% loading condition compared with all other conditions.

Table 3.1 Mean ± SD running velocities in each condition with post-hoc pairwise comparisons.

Condition	Running velocity ($m.s^{-1}$)	p-value vs. 1%	p-value vs. 3%	p-value vs. 5%
BW	4.25 ± 0.43	1	1	0.017
1%	4.25 ± 0.47		1	0.005
3%	4.25 ± 0.48			0.022
5%	4.18 ± 0.44			

BW, body weight; 1%, 1% of body weight WR loading; 3%, 3% of body weight WR loading; 5%, 5% of body weight WR loading.

3.4.1 SPM t-test

Continuous ensemble means per-joint and per-condition with associated standard deviations are presented in Fig 3.3. Sections of significant difference between the BW condition and each loading condition according to SPM t-tests are indicated. WR loading of 1% of body weight led to greater hip extension at 97-99% of the gait cycle (just prior to toe-off) compared with BW ($p = 0.045$). Loading of 3% of body weight resulted in less ankle plantarflexion from 12-18% of the gait cycle (during heel recovery) compared with BW ($p = 0.035$). Loading of 5% of body weight resulted in greater knee flexion from 66-81% of the gait cycle (during weight acceptance) ($p < 0.001$) and less ankle plantarflexion from 9-30% of the gait cycle (during heel recovery) compared with BW ($p < 0.001$). Pointwise t-statistics and the maximum critical value for a significance level of 0.05 for each set of curves are provided in Appendix Table 1.2.

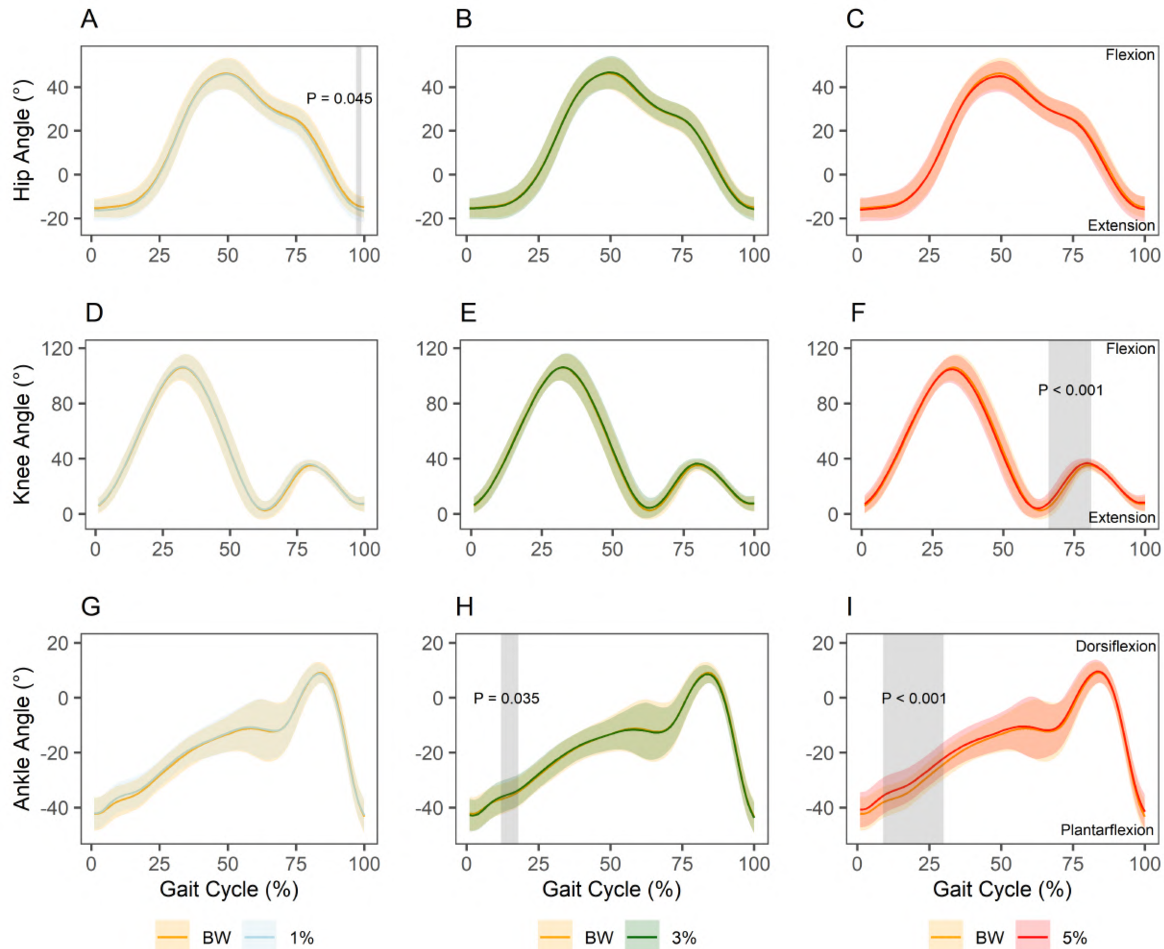

Fig 3.3 SPM t-test per-joint and per-condition versus BW. (A) Hip joint BW versus 1%. (B) Hip joint BW versus 3%. (C) Hip joint BW versus 5%. (D) Knee joint BW versus 1%. (E) Knee joint BW versus 3%. (F) Knee joint BW versus 5%. (G) Ankle joint BW versus 1%. (H) Ankle joint BW versus 3%. (I) Ankle joint BW versus 5%. Solid lines represent ensemble means and accompanying shaded regions represent ± 1 SD. Grey shaded regions indicate regions of significant difference between curve sets.

3.4.2 GAMs

The summary statistics of each joint GAM are shown in Table 3.2. For BW, the estimate indicates the mean joint angle across the stride cycle. For loading conditions, estimates indicate the difference in mean joint angle across the stride cycle versus BW. Estimated degrees of freedom reflect the number of basis functions used to generate the smooths and therefore a higher number of estimated degrees of freedom suggests more variable data. For loading conditions, estimated degrees of freedom are in addition to those listed for BW.

Table 3.2 Generalised additive model summary statistics per-joint.

		Parametric coefficients				Smooth terms		
Joint	**Condition**	**Estimate**	**Standard error**	**t-value**	**Pr(>|t|)**	**EDF**	**F**	**p-value**
Hip	**BW (intercept)**	14.16	1.35	10.5	> 0.001	12.96	22666.3	> 0.001
	1%	-0.65	0.06	-10.99	> 0.001	3.8	4.94	> 0.001
	3%	-0.12	0.06	-2.05	0.04	4.51	3.64	> 0.001
	5%	-0.71	0.06	-11.76	> 0.001	7.62	7.12	> 0.001
Knee	**BW (intercept)**	43.21	1.15	37.65	> 0.001	8	32137.8	> 0.001
	1%	0.55	0.1	5.25	> 0.001	4.05	1.47	0.009
	3%	0.71	0.1	6.86	> 0.001	3.54	7.42	> 0.001
	5%	0.15	0.1	1.48	0.14	7.29	52.18	> 0.001
Ankle	**BW (intercept)**	-18.5	1.06	-17.48	> 0.001	20.85	6141	> 0.001
	1%	0.33	0.07	4.95	> 0.001	5.85	2.6	> 0.001
	3%	-0.15	0.07	-2.18	0.03	3.91	1.77	> 0.001
	5%	1.31	0.07	19.49	> 0.001	5.55	5.06	> 0.001

EDF, estimated degrees of freedom; BW, body weight; 1%, 1% of body weight WR loading; 3%, 3% of body weight WR loading; 5%, 5% of body weight WR loading.

The GAM random effects estimates per-run are shown in Fig 3.4. Random effects estimates reflect the prevailing flexion-extension bias throughout the stride cycle relative to the group mean. The distribution of random effects estimates appeared to be more strongly driven by the participant in question than within-participant responses to WR loading. However, individual-level responses of note include instances in which loading increased between-run variability, such as at the ankle in the 5% condition for F1, the knee in the 5% condition for M1, the knee in the 1% condition for M2, the knee in all loading conditions for M3, the hip and ankle in the 3% condition for F2, and the hip in the 5% condition for M7. Conversely, decreased between-run variability was evident at the ankle in the 3% condition for M1, the ankle in the 3% and 5% conditions for M2, the hip in the 5% condition for M5, the ankle in the 5% condition for F2 and M6, and the ankle in the 1% condition for F3. Shifts in the prevailing random effects estimates on the basis of loading appeared evident at the ankle in the 1% and 3% conditions for M2, the hip in the 3% condition for M3 and F2, the ankle in the 5% condition for M6, the hip in the 3% and 5% conditions for M7, the hip in the 1% condition for F3, and the hip in the 1% and 3% conditions for M11.

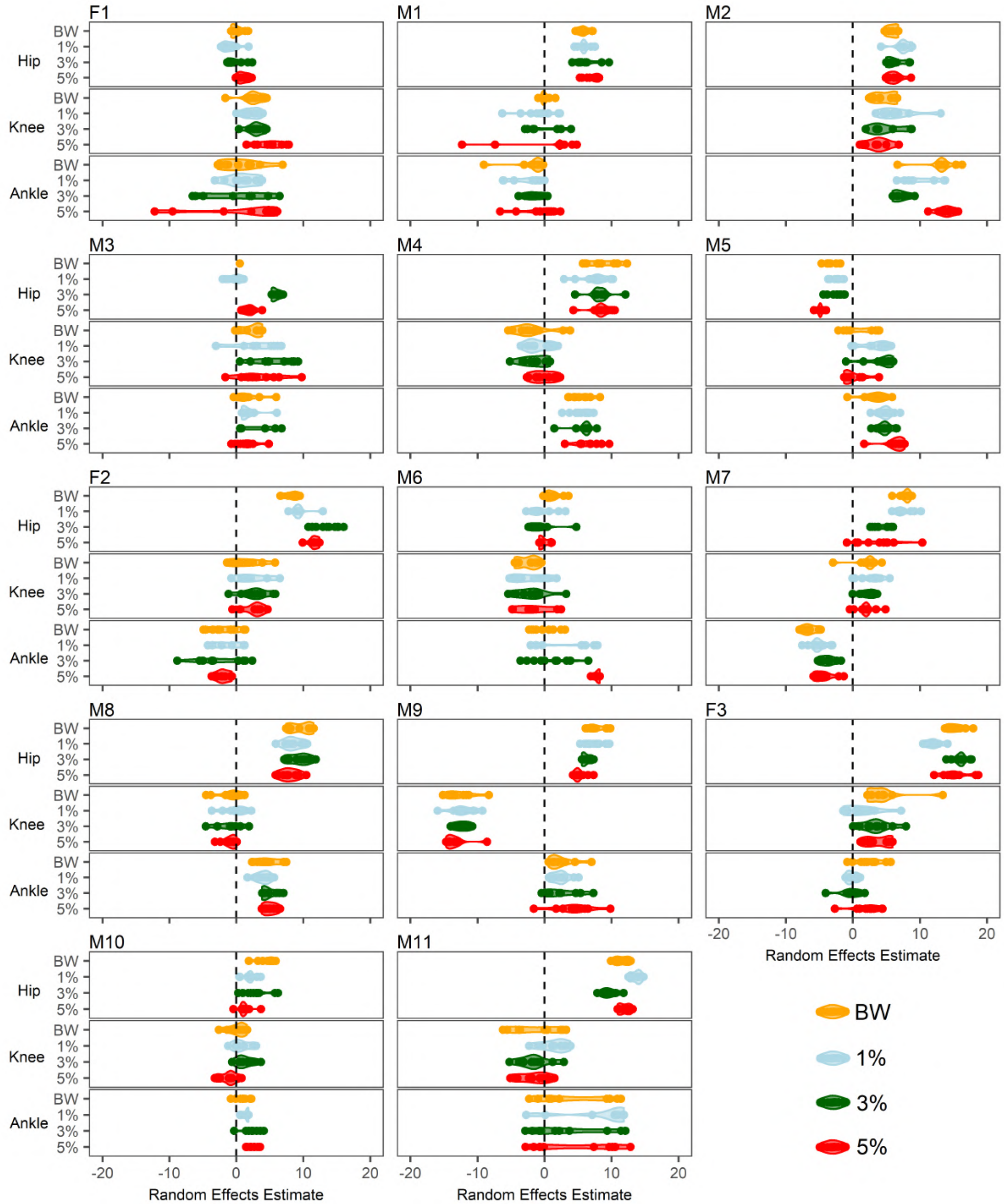

Fig 3.4 GAM random effects estimates per-run, per-individual. Each major panel relates to a given participant, as denoted by labels. Joints are separated by the three minor panels within each participant plot. Conditions are expressed as categories within each joint and associated colours have been included for clarity. Positive estimates indicate greater hip flexion, knee flexion, and ankle dorsiflexion relative to the group mean. Negative estimates indicate greater hip extension, knee extension, and ankle plantarflexion. Thicker regions of

coloured portions reflect a greater concentration of runs with similar random effects estimates.

3.4.3 *bf*PCA

For hip-knee joint coupling, *bf*PC1 explained 41.1% of the variability in the group data (Fig 3.5). Positive scorers on *bf*PC1 exhibited less knee flexion during the swing phase, while negative scorers exhibited greater knee flexion. *bf*PC2 explained 23.3% of the variability in the group data. Positive scorers on *bf*PC2 exhibited greater hip flexion during the swing phase, while negative scorers exhibited less hip flexion and hip flexion was delayed compared with positive scorers. For knee-ankle joint coupling, *bf*PC1 explained 45.6% of the variability in the group data. Positive scorers exhibited less knee flexion during the swing phase and negative scorers exhibited greater knee flexion. *bf*PC2 explained 16.8% of the variability in the group data. Positive scorers on *bf*PC2 exhibited less ankle plantarflexion, particularly at touchdown, while negative scorers exhibited greater ankle plantarflexion during late swing and touchdown.

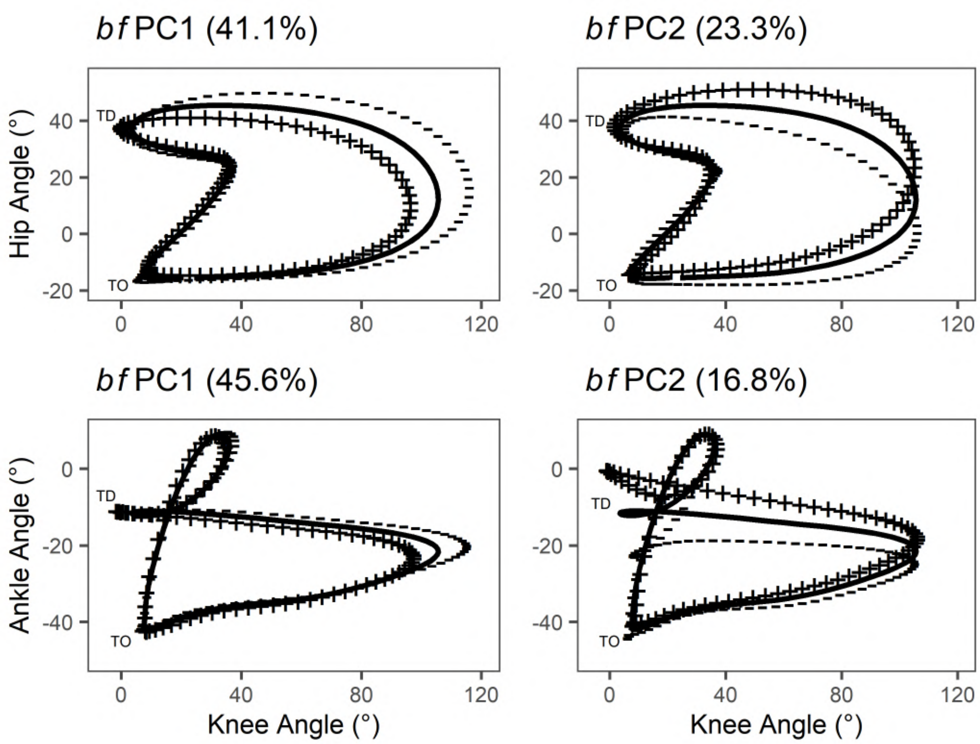

Fig 3.5 *bf*PCA of hip-knee and knee-ankle joint couples throughout stride cycle. First two bfPCs from hip-knee and knee-ankle *bf*PCA with the percentage of group variability

explained. Solid line represents the mean angle-angle curve. '+' line represents positive scorers +2SD from the mean function. '-' line represents negative scorers -2SD from the mean function.

Mean individual *bf*PC scores along both *bf*PCs for hip-knee and knee-ankle joint pairs across runs in each condition are shown in Fig 3.6. Participants appeared to have mostly distinct joint coupling profiles and there was some impact of WR loading within-individuals. There was generally agreement between observations of condition-based shifts in random effects estimates from GAM analysis and differences in mean *bf*PC scores, including in the knee-ankle joint couple in the 3% condition for M2, the hip-knee joint couple in the 3% condition for M3 and F2, the knee-ankle joint couple in the 5% condition for M6, the hip-knee joint couple in the 3% and 5% conditions for M7, and the hip-knee joint couple in the 1% condition for F3 and M11. Additional condition-based shifts apparent from *bf*PCs included the hip-knee joint couple in the 1% condition in M2, the hip-knee joint couple in the 5% condition for M3, M6, M8, and M10, and the knee-ankle joint couple in the 1% condition for M11. Shifts that were identified from GAM analysis but that appeared to be minimal based on *bf*PC plots included the knee-ankle joint couple in the 1% condition for M3 and the hip-knee joint couple in the 3% condition for M11.

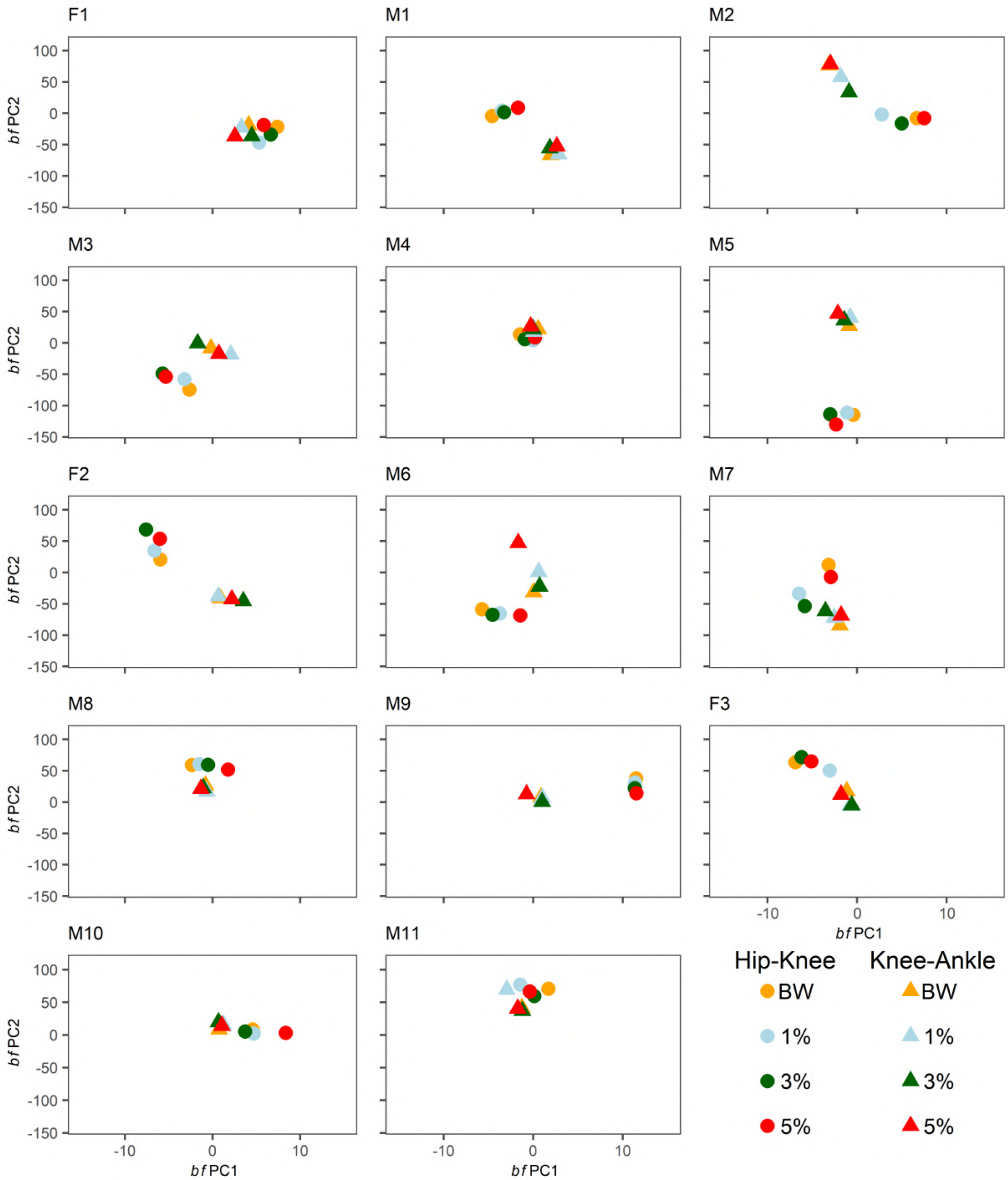

Fig 3.6 Individual mean hip-knee and knee-ankle *bf*PC1 and *bf*PC2 scores per-condition. Each panel relates to a given participant, as denoted by labels. Mean hip-knee *bf*PC scores across runs within a condition are denoted by circle labels. Mean knee-ankle *bf*PC scores across runs within a condition are denoted by triangle labels. Separate conditions are indicated by distinct colours.

3.5 Discussion

This study examined the effects of lower limb WR loading on coordination tendencies during sub-maximal overground running. Specifically, the study sought to describe the effects of various WR magnitudes (1%, 3%, and 5% of body weight) on lower limb sagittal plane joint kinematics at a group- and individual-level, both in terms of continuous gait cycle kinematics and between-run movement variability. The main findings at a group-level were that 3% and 5% loading decreased ankle plantarflexion during heel recovery, while 5% loading also increased knee flexion during weight acceptance, compared with BW running. In terms of joint coupling, 5% loading brought about the largest changes in coordination at the hip-knee joint pair. At an individual-level, six of the fourteen participants clearly exhibited increased between-run joint angle variability at one or more joints in one or more loading conditions compared with BW.

Running velocity was slower in the 5% condition compared with all other conditions, however, the magnitude of this difference was minimal at just 0.07 $m.s^{-1}$. All participants maintained speeds sufficient to successfully complete all shuttles within the allotted time frames in all conditions.

In terms of kinematics at the group-level, slight decreases in ankle plantarflexion during heel recovery occurred with 3% loading compared with BW running. The 5% loading condition led to more substantial decreases in ankle plantarflexion during heel recovery, as well as increased knee flexion during weight acceptance. The exhibition of greater knee flexion was likely a mechanism to mitigate increased peak ground reaction force arising from the greater system load (Liew et al. 2017; Silder et al. 2015). Explanations for less plantarflexion during heel recovery are more speculative. One possibility is that participants subconsciously attempted to offset the greater moment of inertia at the thigh by dorsiflexing the ankle to create a mechanical advantage during swing leg recovery (Jeffreys and Moody 2016; Seagrave et al. 2009). Alternatively, or perhaps in addition, heavier loading likely led to increased co-contraction of muscles around the ankle joint during stance for maintenance of stiffness and stability (Silder et al. 2015; Di Nardo et al. 2016). Such alterations in motor unit recruitment and temporal sequencing of lower leg muscles may constrain the action of this joint during the subsequent propulsion and swing phase, with the joint returning to a relatively more neutral position more readily (Marras et al. 1987; Chmielewski et al. 2005).

The impact of coordination dynamics should also be considered. Individuals performing novel motor tasks often exhibit freezing of distal biomechanical degrees of freedom to reduce coordinative complexity (Vereijken et al. 1992; Bernstein 1967; Southard and Higgins 1987). To the extent that running with an extra 5% of body weight on the lower limbs was perceived as a novel task, there may have been a tendency for participants to return to a more neutral ankle position following toe-off. Given these factors, 5% loading, and to a lesser extent 3% loading, may be excessive as a means of promoting movement variability for some individuals in the first instance. The group-level changes suggest a degree of convergence toward a common adaptation strategy and appear consistent with movement options being limited by task novelty and/or the need to manage high loads. Coaches should take this into consideration if prescribing WR for multiple athletes without individualisation (Bustos et al. 2020).

Despite group-level trends, individual responses varied. The practical utility of WR for inducing movement variability is therefore likely to also be individual-dependent. Coaches should appreciate the range of individual responses and use the present findings as signposts to guide individual WR prescription in the field.

Participants F1, M1, M2, M3, F2, and M7 all exhibited increased between-run variability in mean angles at one or more joints in one or more loading conditions compared with BW. These high variability instances suggest that there was no readily accessible adaptive mode to satisfy the task goal in the presence of WR and instead a period of search and refinement of individuals' preferred coordinative structures was required (Davids et al. 2003a; Davids et al. 2008a). WR in this context therefore provides an opportunity to explore movement system degeneracy. For these individuals, exposure to WR over a training period may facilitate development of movement adaptability and allow running performance to be more readily maintained when perturbations arise in competition (Newell et al. 1989; Barris et al. 2014). The propensity for individuals to exhibit greater variability at one loading condition over another is largely a function of intrinsic behavioural dynamics, which dictate system tendencies such as attractor state stability and behavioural meta-stability (Kelso 2012; Juarrero 1999).

A definitive reduction in between-run variability was present in participants F2 and M6 at the ankle joint in the 5% loading condition. This may align with the proposed group-level hypothesis of distal joint freezing in this condition. While established literature tends to define freezing degrees of freedom as restricted movement of a joint within-trials, low between-trial variability is also indicative of constrained movement (Higuchi et al. 2002; Chow et al. 2007). Among these individuals, the perturbation of 5% loading may have been managed by increasing co-contractions and stiffening muscles of the lower limbs, as occurs in the early stages of skill acquisition (Vereijken et al. 1992). Interestingly, this can be considered an adaptive strategy in itself, particularly since performance of shuttle runs was successfully maintained. This therefore raises the need to clarify the benefit of perturbations that encourage movement variability during training versus those that limit movement variability. Findings from balance beam walking with different perturbation magnitudes demonstrate that learning under conditions in which sacral movement variability is maximised leads to superior learning and subsequent task performance post-training (Domingo and Ferris 2010). Substantially increasing the level of perturbation through an error augmenting device decreases movement variability in line with individuals attempting to maintain control of movement, and has suboptimal outcomes for post-training performance (Domingo and Ferris 2010). Separately, Chmielewski *et al*. (Chmielewski et al. 2005) argue that increased co-contractions as a means of adapting to an ACL rupture reflect a suboptimal compensation pattern wherein the capacity to dynamically stabilise the injured knee without compromising knee motion has not yet been developed. Taken together, these findings highlight that large magnitude perturbations may be adapted to by reducing movement variability, however, skill acquisition is not facilitated under these conditions. Reduced movement variability affords fewer opportunities for internal models of limb dynamics to be updated, which may limit the extent to which adaptability is trained (Wolpert and Ghahramani 2000).

Among high performing field-based athletes, some individuals are likely to already have well developed functional movement adaptability (Schorer et al. 2007; Chow et al. 2006a). This is typified by an appropriate mix of movement pattern flexibility and stability, such that coordination can be readily adjusted in response to a perturbation and movement variability levels remain similar to those at baseline (Newell and Corcos 1991; Barris et al. 2014). Potential exemplars of this in the present study include participant M10 in all loading conditions and participant M7 in the 3% loading condition.

Participants M4 and M9 exhibited no discernable joint kinematic changes at any loading magnitude. Between-run variability also appeared consistent across loading. For these individuals, loading even up to 5% of body weight may not have required additional exploitation of movement system degeneracy to satisfy the task goal (Edelman and Gally 2001). As part of their intrinsic behavioural dynamics, these individuals likely defer to highly stable movement attractor states in the presence of manageable perturbations (Kelso 1995; Davids et al. 2003a). Practically, WR may not be appropriate to challenge running coordination among such individuals, as loading beyond 5% of body weight on the lower limbs presents logistical difficulties due to load placement space limitations.

Lastly, it is interesting to note that participants M2 and M11 appeared to demonstrate multi-stability about the ankle joint. There appeared to be two dominant kinematic modes expressed with apparent condition dependence in M2 but not in M11. Coaches should appreciate that athletes may exhibit multi-stability, wherein two or more patterns of coordination are stable (Kelso 2012).

A limitation of the present study is that only sagittal plane kinematics were considered. Consequential alterations to kinematics may have also occurred in the transverse and frontal planes, or in trunk or upper body segments. In terms of the WR, an exactly equal distribution of load between the anterior and posterior segment surfaces could not always be guaranteed. In these instances, one surface of each segment experienced 50 g more loading, which although minimal, may have impacted ensuing running kinematics. In relation to data processing, it is important to acknowledge that although the initial rise in vertical displacement of the toe marker has previously been used to define toe-off during running actions (Bezodis et al. 2007; Nagahara and Zushi 2013; Schache et al. 2001), validation of this detection method against force plate measures under the specific running velocities and floor surface conditions of the present study has not been performed. Lastly, despite the 3 min rest period allowed between running trials, residual after-effects following heavier loading conditions could have briefly impacted on the kinematics observed during lighter conditions (Nakamoto et al. 2012). When SPM t-tests were repeated with participants separated on the basis of having completed the 1% condition immediately following the 5% condition as part of their randomisation, it was evident that the group-level differences in hip extension between the 1% condition and BW were driven by these participants

(Appendix Fig 1.1). A larger sample size would provide clarity on this point by enabling direct statistical comparisons between participants who experienced the 1% condition immediately following the 5% condition, and those that did not. If this type of loading contrast was an effectual factor, fidelity could be improved by allowing participants to rest for longer or briefly run without loading in between trials to "re-establish" an unloaded baseline.

Future research should specifically consider the effects of unloaded running immediately following a period of loading to clarify the propensity for acute coordinative changes to be retained following the removal of perturbation. Investigation into the impact of asymmetrical WR loading on coordination would also be worthwhile given the challenge to the movement system that such an intervention would pose. As understanding of the effects of WR loading develops, researchers and/or coaches should consider situating tasks such as loaded running in a representative, field-based environment. WR coupled with the inherent movement variability induced by dynamic constraints and affordances in this environment would present a further, more contextual, challenge to coordination (Araújo et al. 2006).

3.6 Conclusions

Exposure to WR of 5% of body weight increased knee flexion during weight acceptance and decreased ankle plantarflexion during heel recovery at the group-level. This appeared to be due to the high load and novelty of this condition. Among individuals that reflected group-level trends and exhibited decreased between-run variability at one or more joints, 5% loading may be an excessive perturbation, as exploration of alternate movement states is limited. However, this loading magnitude may have utility in other contexts, such as overloading rotational work at the hip joint over a given running distance.

Several participants exhibited increased between-run joint angle variability in one or more loading conditions compared with BW, suggesting exploration and refinement of coordinative structures under these conditions. The loading magnitudes at which these increases were elicited, however, varied between individuals. WR therefore appears to show utility for the purpose of perturbing coordination to encourage movement variability among certain individuals, though the loading magnitudes used should be determined on a case-by-case and goal-dependent basis.

Chapter 4 – The influence of lightweight wearable resistance on whole body coordination during sprint acceleration among Australian Rules football players

4.1 Abstract

Rapid acceleration is an important quality for field-based sport athletes. Technical factors contribute to acceleration and these can be deliberately influenced by coaches through implementation of constraints, which direct movement towards particular coordinative states or induce variability generally. Lightweight wearable resistance is an emerging training tool, which can act as a constraint on acceleration. At present, however, the effects on whole body coordination resulting from wearable resistance application are unknown. To better understand these effects, five male Australian Rules football athletes performed a series of 20 m sprints with either relatively light or heavy wearable resistance applied to the anterior or posterior aspects of the thighs or shanks. Whole body coordination during early acceleration was examined across eight wearable resistance conditions and compared with baseline (unresisted) acceleration coordination using group- and individual-level hierarchical cluster analysis. Self-organising maps and a joint-level distance matrix were used to further investigate specific kinematic changes in conditions where coordination differed most from baseline. Across the group, relatively heavy wearable resistance applied to the thighs resulted in the greatest difference to whole body coordination compared with baseline acceleration. On average, heavy posterior thigh wearable resistance led to altered pelvic position and greater hip extension, while heavy anterior thigh wearable resistance led to accentuated movement at the shoulders in the transverse and sagittal planes. These findings offer a useful starting point for coaches seeking to use wearable resistance to promote adoption of greater hip extension or upper body contribution during acceleration. Importantly, individuals varied in how they responded to heavy thigh wearable resistance, which coaches should be mindful of.

4.2 Introduction

The ability of athletes to rapidly accelerate is an important quality required in many field-based sports. On average, soccer, rugby league, and Australian football athletes perform between 50-100 acceleration efforts (>2.87 $m.s^{-2}$ (Sweeting et al. 2017)) throughout match play (Varley and Aughey 2013; Coutts et al. 2015). In addition, these efforts are often associated with critical events, such as winning the ball or breaking away from an opponent (Reilly et al. 2000a; Rienzi et al. 2000). A key role of strength and conditioning coaches in these sports is therefore to develop the kinetic and kinematic factors that contribute to acceleration performance, such as horizontal and vertical ground reaction impulse (GRI) and body segment positions (Murphy et al. 2003; Hunter et al. 2004; Buchheit et al. 2014).

Training programs aiming to improve sprint acceleration usually incorporate a combination of exercises targeted towards achieving neuromuscular overload, as well as drills to improve sprint technique (Jones et al. 2016; Nicholson et al. 2022). While the effects of various overload interventions on acceleration kinetics, kinematics, and performance among field-based athletes have been extensively researched (Wilson et al. 1993; Chelly et al. 2015; Marques et al. 2015; Speirs et al. 2016; Contreras et al. 2017), less attention has been paid to training drills aimed at altering sprint technique. This is despite findings that highlight the importance of technical execution in acceleration (Kugler and Janshen 2010; Morin et al. 2011). For example, faster individuals exhibit a greater magnitude anteroposterior component of resultant ground reaction forces (GRFs) during acceleration than slower individuals (Kugler and Janshen 2010; Morin et al. 2011). This contributes to more forward oriented GRFs and superior performance, despite negligible differences in the magnitude of GRFs between the two. This is achieved through foot touchdown more posterior relative to the centre of mass (Kugler and Janshen 2010). Coaches may therefore seek to understand the coordination patterns associated with faster acceleration on an individual basis and aim to train technique in accordance with the expression of such patterns.

Traditional strength and conditioning approaches to sprint technique training have often utilised deconstructed, part practice drills to target a particular aspect of coordination (Cameron et al. 2009; Pinske et al. 2012). Modern skill acquisition perspectives, however, advocate the use of pedagogical approaches, which consider movement as an emergent property of a complex system (Handford et al. 1997; Kiely 2011; Bosch 2015; Moy et al.

2020). Constraints on complex systems direct emergent behaviour by limiting the behavioural trajectories that can be adopted (Newell 1986; Thelen 1995). Constraints therefore represent control parameters, which can be manipulated by coaches to influence specific movement behaviours that may benefit performance, or to induce general variability and encourage exploration of movement (Davids et al. 2006b; Renshaw et al. 2019). Both the use of constraints to shape movement, and the use of constraints to induce variability have demonstrated effectiveness as far as altering coordination patterns and improving performance in a number of sporting tasks (Wagner and Müller 2008; Gray 2020; Moy et al. 2020; Verhoeff et al. 2018).

While there are innumerable constraints that can be imposed to influence sprint acceleration movement organisation, lightweight wearable resistance (WR) is an increasingly popular training tool with possible applications for this purpose. Modern iterations of WR involve attachment of small weights to particular body segments, such as the trunk, arms, thighs, and shanks (Simperingham and Cronin 2014; Macadam et al. 2017b; Feser et al. 2018a; Hurst et al. 2018; Macadam et al. 2019a; Macadam et al. 2019b; Uthoff et al. 2020; Macadam et al. 2020b; Trounson et al. 2020). To date, most WR research in sprinting has sought to examine the effects of WR as a movement specific overload stimulus (Simperingham and Cronin 2014; Simperingham et al. 2016; Macadam et al. 2017b; Feser et al. 2018a; Hurst et al. 2018; Macadam et al. 2019b; Simperingham et al. 2020; Macadam et al. 2020b). Decrements in sprint speed or changes in particular whole body spatiotemporal gait parameters are seen as indicating overload has occurred (Macadam et al. 2017b; Hurst et al. 2018; Feser et al. 2018a; Macadam et al. 2019b; Simperingham et al. 2020; Macadam et al. 2020b). The focus on WR as a neuromuscular overload tool overlooks its potential use as a coaching tool to alter coordination in a complex systems-based pedagogical framework. While some studies have hinted at this application, suggesting that WR could reinforce piston-like mechanics required during acceleration for example (Simperingham et al. 2015; Macadam et al. 2019a), only a limited number (Zhang et al. 2018; Hurst et al. 2020; Macadam et al. 2021b; Macadam et al. 2021a; Feser et al. 2023) have actually investigated joint-level kinematic changes induced by WR. Besides directing movement towards favourable patterns, it is also conceivable that WR implementation may destabilise preferred patterns, inducing movement variability. Variability in training can facilitate adaptability, i.e. task execution across more varied contexts, which is advantageous for field-based athletes encountering dynamic and unpredictable scenarios in match play (Lee et al. 2014; Orth et al. 2017). Given the lack of predictability about movement alterations in response to WR, the present study adopted a broad analytical approach, which considered changes to continuous time series angle data across multiple joints and planes during early acceleration in response to WR. Initial characterisation of the whole body coordination changes that occur may offer a starting point for coaches in applied settings interested in using WR in a skill acquisition context. This study therefore aimed to determine the extent and manner of whole body coordination changes during sprint acceleration arising from different WR loading configurations and magnitudes among Australian Rules football players, with consideration for both group-level and within-individual changes.

4.3 Materials and methods

4.3.1 Participants

Five semi-professional male Australian Rules football players (mean ± SD; age: 21.2 ± 4.1 years; height: 180.6 ± 6.5 cm; body mass: 72.0 ± 4.3 kg) were recruited between July 30 and October 15 2019 for participation in this study. Participants are hereafter denoted as P1-P5. For inclusion in the study, participants were required to be currently playing at a semi-professional level, undertaking structured team training twice per week and match play once per week, and have had no prior experience with WR. On average, players of this level are exposed to 25-40 km total running distance across a week, with 3-5 km of this volume occurring at speeds of 20 km/h or greater (Johnston et al. 2015; Johnston et al. 2018). All participants provided written informed consent and were free from musculoskeletal injury at the time of, and in the 6 months prior to, testing. All procedures used in this study complied with the criteria of the declaration of Helsinki and ethical approval was granted by the Victoria University Human Research Ethics Committee (HRE19-020).

4.3.2 Procedure

4.3.2.1 Study design

Testing was undertaken in ambient temperature (24 ± 2ºC) in the Biomechanics Laboratory at Victoria University, Footscray Park, Melbourne, Australia. Participants attended the laboratory on 10 occasions in total, comprising one familiarisation session, one baseline testing session, and eight WR testing sessions. Each testing session was conducted at the same time (09:00 AM) to minimise the influence of circadian variation and was undertaken at least 48 hours post-previous match play or structured team training. Each testing session was separated by at least 1 week. During testing sessions, participants undertook a warm-up, which consisted of a series of dynamic mobility drills, including; forward lunges with arm reaches, leg swings, lateral lunges, and tiptoe walks, executed as previously described (Saraswate et al. 2018). These drills were followed by four sub-maximal 20 m sprints. The 15-grade Borg scale rating of perceived exertion scale (Borg 1982) was explained to participants, and instruction was given to perform the four warm-up sprints corresponding to "fairly light", "somewhat hard", "hard", and "very hard" levels of exertion, respectively. Following this, participants performed four maximal 20 m sprints commencing from a stationary position, interspersed with 3 min rest periods. During WR testing sessions, participants were exposed to one of eight unique WR loading configurations and magnitudes when performing sprints 2-4. The order of exposure to each WR loading configuration and magnitude was randomised. In each sprint, 10 m split and 20 m sprint times were recorded and whole body spatiotemporal measures and joint kinematics were captured at the 4 m mark to examine coordination during the early acceleration phase of sprinting (Maulder et al. 2008).

4.3.2.2 Experimental setup

A 20 m section of the Biomechanics Laboratory with Mondo track surface defined the sprint area. Infrared timing gates (Smart Speed, Fusion Sport, Brisbane, Australia) were situated at the 0, 10, and 20 m marks along the sprint area. For each sprint, participants adopted a self-selected 2-point upright starting stance with the front foot 0.9 m behind the starting line. Timing began when the timing gates at the 0 m mark were triggered by the participant commencing their sprint. Motion analysis cameras were arranged around the 4 m mark and the approximate capture volume was 5.0 m long, 2.5 m high, and 3.0 m, wide. A 10-camera VICON motion analysis system (T-40 series, Vicon Nexus v2, Oxford, UK) sampling at 250 Hz was used for collection of whole body spatiotemporal and joint kinematic data. A total of 58 reflective markers with 12.7 mm diameter were attached to body landmarks on the upper arms, trunk, pelvis, thighs, shanks, and feet according to the Plug-In-Gait model (Plug-In-Gait Marker Set, Vicon, Oxford, UK) (Fig 4.1). In Vicon Nexus software, a global reference system was defined with the positive Y-axis horizontal in the direction of the sprint, the positive X-axis perpendicular to the Y-axis – horizontal in the right direction, and the positive Z-axis in the vertical direction.

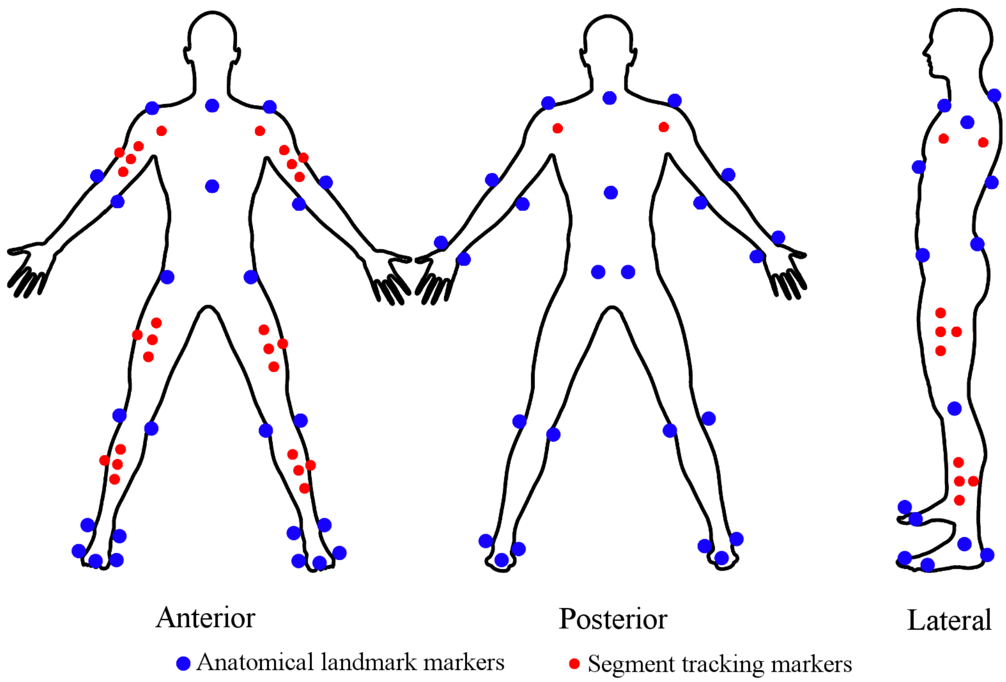

Fig 4.1 Upper- and lower-body Plug-In-Gait model marker placements. Blue markers define the required anatomical landmarks, red markers are used for tracking segments. Adapted from Trounson KM, Busch A, French Collier N, Robertson S (2020) Effects of acute wearable resistance loading on overground running lower body kinematics. PLoS ONE 15(12): e0244361 under a CC BY license, with permission from PLoS ONE, original copyright 2020.

4.3.2.3 Wearable resistance

Throughout testing, participants wore Lila™ Exogen™ (Sportboleh Sdh Bhd, Kuala Lumpur, Malaysia) compression shorts and calf sleeves. During WR exposure trials, a combination of 50, 100, and 200 g fusiform shaped loads (with Velcro backing) totalling the required loading magnitude were attached to the compression garments (Fig 4.2). Four loading configurations were investigated – anterior thigh, posterior thigh, anterior shank, and posterior shank – with both "light" and "heavy" loading magnitudes in each, totalling eight WR conditions. "Light" and "heavy" loading magnitudes corresponded to an increase of 3% and 6% in the moment of inertia about the hip throughout an acceleration stride, respectively, in accordance with sagittal plane lower limb motion previously observed during early acceleration (Debaere et al. 2013). Participant height and weight was used to determine the specific loading magnitudes required at each segment to satisfy these conditions based on Plagenhoef's (Plagenhoef et al. 1983) estimations of segment parameters. Table 4.1 provides an example of the loading magnitudes per leg for a 180 cm, 70 kg male (Plagenhoef et al. 1983). Fusiform loads were added at the midpoint of each segment in a longitudinal formation and in an alternating fashion between a proximal-dominant and distal-dominant orientation. The smallest number of possible loads to achieve the required loading magnitude was used.

Fig 4.2 Lila™ Exogen™ compression calf sleeves with anterior shank loading. Reprinted from Trounson KM, Busch A, French Collier N, Robertson S (2020) Effects of

acute wearable resistance loading on overground running lower body kinematics. PLoS ONE 15(12): e0244361 under a CC BY license, with permission from PLoS ONE, original copyright 2020.

Table 4.1 Example loading magnitudes for a 180 cm, 70 kg male participant.

	Magnitude	
Configuration	**Light (g per leg)**	**Heavy (g per leg)**
Anterior thigh	550	1100
Posterior thigh	550	1100
Anterior shank	250	500
Posterior shank	250	500

4.3.2.4 Data collection

Following application of compression garments, attachment of reflective markers, and the warm-up participants performed four maximal 20 m sprints, each separated by 3 mins rest. The only instruction provided to participants was to sprint as fast as possible. In WR testing sessions, researchers applied the requisite WR loads to the participant during the rest period between the first and second sprint, and the WR was left on for the remaining three sprints. Fig 4.3 provides a summary schematic of the between- and within-testing session structure for a 180 cm, 70 kg participant.

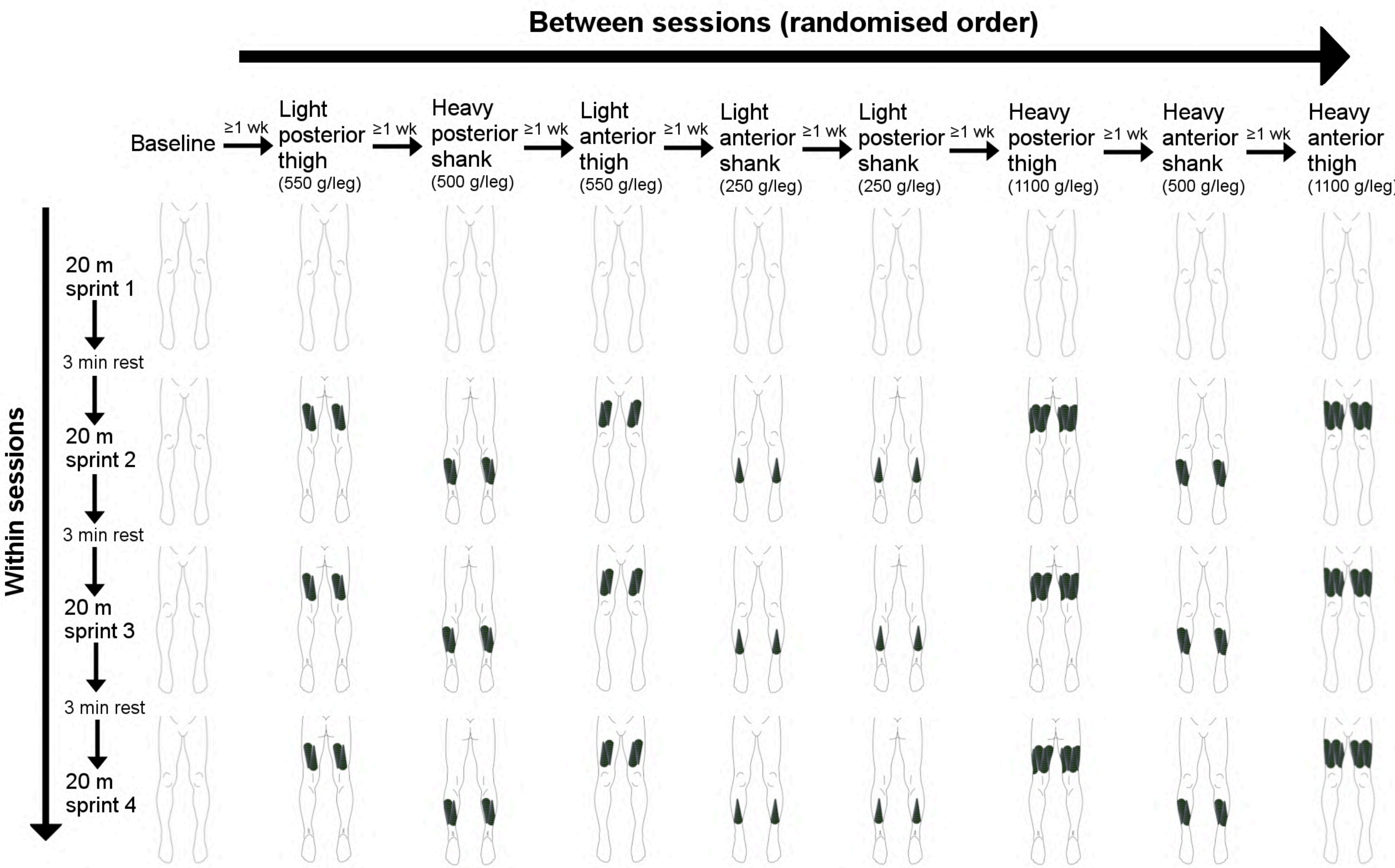

Fig 4.3 Summary of the between- and within-testing session structure for a 180 cm, 70 kg participant. WR conditions were randomised across eight testing sessions separated by at least 1 week. Within testing sessions, participants performed four maximal 20 m sprints interspersed with 3 min rest periods. In all testing sessions the first sprint was performed without WR.

4.3.3 Data processing

Raw marker data were labelled in Vicon Nexus with cubic spline filling used in instances of marker drop out (up to a maximum of 10 frames). Marker data were then transferred to Visual 3D software (C-motion, Rockville, MD, USA) for calculation of whole body spatiotemporal measures and joint kinematics using the following steps. Marker trajectories were smoothed via a fourth order low-pass Butterworth filter with 10 Hz cut-off frequency, based on mean results of residual analyses (Winter 2009). A 10-segment model (upper arms, trunk, pelvis, thighs, shanks, and feet) was then constructed for each participant. Each sprint was trimmed to one complete stride cycle, which was defined as the period between two consecutive toe-off events on the same limb. Toe-off was defined by the initial rise in vertical displacement of the toe marker proceeding its lowest point at the end of the stance phase and these timepoints were automatically detected using an event detection algorithm in Visual 3D (Schache et al. 2001; Nagahara and Zushi 2013). Without explicit instruction, all participants chose to commence sprints with the left foot forward. Analysis was therefore able to be carried out on the stride defined by left foot toe-off to left foot toe-off corresponding to steps 3 and 4 of the sprint effort. This stride was taken as representative of the first phase of acceleration identified by Nagahara et al., (2014), who reported, on average, a definitive breakpoint in acceleration kinematics beyond step 4 (Nagahara et al. 2014). Of the 180 captured sprints, only three were unable to be successfully reconstructed according to the above process and these were excluded from analysis. In all instances, sprints 2-4 from each testing session were used when comparing effects between conditions, unless otherwise stated.

For whole body spatiotemporal measures, an in-built model based function in Visual 3D was used to calculate mean centre of mass (COM) velocity across the stride (Hunter et al. 2004). Flight time was defined as the point of take-off from one foot to the point of ground contact on the contralateral foot. Ground contact time was defined as the point of initial ground contact until the point of take-off on the same foot. Step length was defined as the horizontal distance between successive toe-off events of each contralateral foot. Flight time, ground contact time, and step length were all calculated as an average across the two steps composing the stride cycle (Clark et al. 2010a). Step frequency was defined as the number of steps taken per second and was calculated as the inverse of stride duration multiplied by two.

For joint kinematics, sagittal, frontal, and transverse plane angles were computed from the transformation between two adjacent segments' local coordinate systems described by an XYZ Cardan sequence of rotations (Selbie et al. 2014). These computations were performed in Visual 3D using the in-built joint angle model based function. The following joints/segments were included: pelvis, thorax, right and left side hips, knees, ankles, and shoulders. In all cases, proximal segments were used as reference segments, except for the pelvis in which angles were defined in relation to the global reference frame. A total of 30 kinematic variables therefore contributed to defining whole body coordination profiles. All angles were normalised to 101 data points (0-100% of the stride cycle) prior to further analysis.

4.3.4 Data analysis

4.3.4.1 Descriptive statistics

Mean and standard deviation of 10 m split time, 20 m sprint time, COM velocity at 4 m, and spatiotemporal measures (flight time, ground contact time, step length, and step frequency) were calculated for each participant within conditions and across the five participants.

4.3.4.2 Hierarchical agglomerative clustering

Hierarchical agglomerative clustering was used to visualise the degree of (dis)similarity of whole body coordination between conditions both at the group level and within-participants. This process yields a dendrogram in which the height of the merger between clusters indicates the degree of similarity or dissimilarity between objects. Objects in this instance were the aggregated kinematic variables collected during sprints in each condition. A higher merger between the aggregated kinematic variables across sprints in two different conditions was considered indicative of greater dissimilarity in whole body coordination between the conditions.

For hierarchical agglomerative clustering of kinematic variables between conditions at the group level, the 30-dimensional vectors (10 joints/segments x 3 degrees of freedom) obtained from joint angles in each sprint were averaged across sprints and participants within each condition (15 sprints per condition in total) to produce nine 30-dimensional input variables (v):

$$v_i = \psi_i,1(t) \ldots, \psi_i,30(t) \quad (1)$$

where ψk represents the kinematic variable (k = 1, …, 30). The index, i, represents the condition (i = 1, …, 9), while the time index, t, runs from 0 to 101. Using R (version 3.6.0), data were scaled using z-score standardisation to ensure differences in joint range of motion did not disproportionately influence clustering outcomes. A distance matrix was then created using the Euclidean distance dissimilarity measure. The single linkage hierarchical clustering algorithm was used to generate the clustering hierarchy and dendrogram. Code for this analysis is provided at https://github.com/ktrounson/WR-acceleration/blob/main/Group-hclust.

Hierarchical agglomerative clustering of kinematic variables between conditions within-individuals followed the same process as above, however, vectors were averaged only across sprints in each condition (heavy anterior thigh, light anterior thigh, heavy posterior thigh, light posterior thigh, heavy anterior shank, light anterior shank, heavy posterior shank, light posterior shank). Averaging three sprints per condition within each participant produced 45 30-dimensional input variables. Code used for this analysis is provided at https://github.com/ktrounson/WR-acceleration/blob/main/Indiv-hclust.

4.3.4.3 Self-organising map

A self-organising map (SOM) analysis was used to investigate whole body coordination profiles across the course of the stride cycle (Schöllhorn et al. 2013). The SOM effectively represents the whole body coordination throughout the stride cycle for each participant on a two-dimensional grid. Patterns that are similar to one another in the original kinematic space are mapped closer to one another in the two-dimensional SOM space. Following scaling, each sprint was inputted as a 30-dimensional vector into the SOM algorithm available in the R *kohonen* package (Wehrens and Buydens 2007). The training process adopted a linearly decreasing learning rate from $\alpha = 0.05$ to $\alpha = 0.01$ and a Gaussian neighbourhood function. The final SOM was projected on a 40x40 hexagonal lattice output space and visualised as a unified distance matrix (U-matrix). The SOM code used is provided at https://github.com/ktrounson/WR-acceleration/blob/main/SOM. In the U-matrix, cells are shaded based on the distances to immediate neighbours. Darker shaded areas have a smaller distance to neighbours and correspond with greater convergence of movement patterns in these areas. The two WR conditions in which there was the most dissimilar whole body coordination compared with baseline (based on the results of hierarchical clustering) were considered to be of particular interest for further analysis and discussion. Best-matching unit trajectories for each participant in these conditions were included in the results section, while best-matching unit trajectories for each participant in the remaining conditions were included as supplementary figures.

4.3.4.4 Joint-level distance matrix

For the two most dissimilar conditions to baseline identified from group-level hierarchical clustering, an additional distance matrix was constructed to determine the specific joints most impacted by WR loading. Each time-continuous joint angle was averaged across sprints and participants within each condition, and was used as a separate input variable. Data was scaled using z-score standardisation and a Euclidean distance dissimilarity measure was used to generate the distance matrix. A greater distance between the same joint and plane under different conditions was interpreted as greater dissimilarity in the specific motion of the joint. Code for the joint-level distance matrix analysis is provided at https://github.com/ktrounson/WR-acceleration/blob/main/Joint-distance.

4.4 Results

4.4.1 Descriptive statistics

Means and standard deviations of 20 m sprint time and whole body spatiotemporal measures for each participant and across the group are displayed in Table 4.2. Means and standard deviations of 10 m split times and COM velocity at 4 m are provided in Appendix Table 2.1.

Table 4.2 20 m sprint times and whole body spatiotemporal measures (mean ± SD).

		Baseline	HAT	LAT	HPT	LPT	HAS	LAS	HPS	LPS
20 m sprint time (s)	P1	3.27 ± 0.06	3.32 ± 0.02	3.31 ± 0.04	3.35 ± 0.06	3.24 ± 0.06	3.32 ± 0.04	3.26 ± 0.04	3.29 ± 0.05	3.33 ± 0.05
	P2	3.51 ± 0.03	3.57 ± 0.08	3.65 ± 0.05	3.62 ± 0.05	3.55 ± 0.04	3.60 ± 0.05	3.57 ± 0.02	3.56 ± 0.04	3.61 ± 0.01
	P3	3.25 ± 0.06	3.32 ± 0.03	3.22 ± 0.02	3.19 ± 0.02	3.24 ± 0.03	3.29 ± 0.01	3.28 ± 0.07	3.33 ± 0.05	3.42 ± 0.07
	P4	3.19 ± 0.04	3.26 ± 0.03	3.19 ± 0.02	3.19 ± 0.01	3.19 ± 0.01	3.18 ± 0.01	3.22 ± 0.04	3.23 ± 0.02	3.17 ± 0.01
	P5	3.33 ± 0.05	3.30 ± 0.01	3.30 ± 0.01	3.40 ± 0.01	3.28 ± 0.01	3.29 ± 0.02	3.36 ± 0.01	3.23 ± 0.03	3.26 ± 0.05
	Group	3.31 ± 0.12	3.36 ± 0.12	3.34 ± 0.17	3.35 ± 0.17	3.30 ± 0.14	3.34 ± 0.15	3.34 ± 0.13	3.34 ± 0.12	3.36 ± 0.16
Flight time (ms)	P1	85 ± 8	100 ± 7	80 ± 17	88 ± 19	83 ± 8	92 ± 4	85 ± 8	77 ± 2	84 ± 17
	P2	83 ± 7	88 ± 8	79 ± 5	76 ± 4	80 ± 4	88 ± 4	85 ± 5	81 ± 8	79 ± 5
	P3	81 ± 10	91 ± 2	81 ± 2	83 ± 5	76 ± 11	84 ± 4	80 ± 8	92 ± 7	81 ± 5
	P4	81 ± 9	80 ± 8	84 ± 4	85 ± 2	84 ± 7	83 ± 6	81 ± 13	83 ± 2	77 ± 2
	P5	93 ± 6	104 ± 8	84 ± 11	88 ± 4	99 ± 20	84 ± 7	76 ± 4	95 ± 6	96 ± 1
	Group	85 ± 8	93 ± 11	82 ± 8	84 ± 9	84 ± 13	86 ± 6	82 ± 8	86 ± 8	83 ± 10
Ground contact time (ms)	P1	136 ± 4	136 ± 4	151 ± 6	145 ± 8	140 ± 4	133 ± 6	137 ± 2	140 ± 4	147 ± 5
	P2	165 ± 6	167 ± 2	171 ± 2	177 ± 5	169 ± 2	169 ± 5	164 ± 4	172 ± 8	173 ± 2

	P3	167 ± 5	167 ± 6	175 ± 2	164 ± 4	169 ± 10	168 ± 1	167 ± 14	169 ± 6	179 ± 2
	P4	131 ± 9	131 ± 10	131 ± 6	125 ± 2	128 ± 7	128 ± 4	135 ± 10	123 ± 5	129 ± 2
	P5	156 ± 4	149 ± 6	165 ± 10	163 ± 8	161 ± 8	173 ± 6	172 ± 4	160 ± 7	158 ± 3
	Group	151 ± 16	150 ± 16	158 ± 17	155 ± 19	154 ± 18	154 ± 21	155 ± 18	153 ± 20	157 ± 19
Step length (m)	**P1**	1.34 ± 0.03	1.42 ± 0.06	1.36 ± 0.09	1.37 ± 0.03	1.33 ± 0.04	1.36 ± 0.03	1.39 ± 0.03	1.32 ± 0.03	1.35 ± 0.11
	P2	1.40 ± 0.01	1.42 ± 0.03	1.39 ± 0.03	1.40 ± 0.05	1.38 ± 0.03	1.45 ± 0.01	1.39 ± 0.01	1.40 ± 0.02	1.44 ± 0.01
	P3	1.49 ± 0.03	1.50 ± 0.05	1.54 ± 0.01	1.51 ± 0.03	1.49 ± 0.02	1.51 ± 0.02	1.50 ± 0.03	1.52 ± 0.04	1.54 ± 0.03
	P4	1.27 ± 0.05	1.23 ± 0.06	1.27 ± 0.01	1.24 ± 0.01	1.26 ± 0.02	1.28 ± 0.02	1.28 ± 0.06	1.24 ± 0.03	1.24 ± 0.01
	P5	1.42 ± 0.07	1.50 ± 0.04	1.36 ± 0.03	1.47 ± 0.05	1.58 ± 0.05	1.42 ± 0.02	1.38 ± 0.04	1.46 ± 0.07	1.54 ± 0.01
	Group	1.38 ± 0.09	1.41 ± 0.11	1.39 ± 0.10	1.40 ± 0.10	1.41 ± 0.12	1.40 ± 0.08	1.39 ± 0.08	1.39 ± 0.11	1.41 ± 0.13
Strep frequency (Hz)	**P1**	4.42 ± 0.13	3.99 ± 0.04	4.35 ± 0.28	4.15 ± 0.16	4.50 ± 0.24	4.27 ± 0.17	4.26 ± 0.11	4.49 ± 0.09	4.37 ± 0.49
	P2	3.87 ± 0.09	3.81 ± 0.09	3.77 ± 0.07	3.79 ± 0.06	3.89 ± 0.13	3.68 ± 0.05	3.97 ± 0.06	3.83 ± 0.03	3.83 ± 0.09
	P3	3.90 ± 0.18	3.70 ± 0.18	3.93 ± 0.16	3.91 ± 0.11	4.04 ± 0.20	3.77 ± 0.03	3.87 ± 0.03	3.77 ± 0.03	3.72 ± 0.12
	P4	4.48 ± 0.26	4.34 ± 0.04	4.60 ± 0.13	4.49 ± 0.05	4.41 ± 0.12	4.55 ± 0.01	4.40 ± 0.35	4.47 ± 0.08	4.57 ± 0.10
	P5	3.80 ± 0.14	3.73 ± 0.10	3.79 ± 0.15	3.83 ± 0.09	3.74 ± 0.25	3.89 ± 0.03	3.95 ± 0.09	3.83 ± 0.03	3.88 ± 0.13
	Group	4.11 ± 0.33	3.91 ± 0.26	4.09 ± 0.37	4.03 ± 0.28	4.12 ± 0.35	4.03 ± 0.35	4.09 ± 0.26	4.08 ± 0.34	4.09 ± 0.41

HAT, heavy anterior thigh; LAT, light anterior thigh; HPT, heavy posterior thigh; HAS, heavy anterior shank; LAS, light anterior shank; LPS, light posterior shank; HPS, heavy posterior shank; LPT, light posterior thigh; COM, centre of mass.

4.4.2 Hierarchical agglomerative clustering

Group-level whole body coordination cluster analysis revealed that coordination in light WR conditions tended to be more similar to baseline, as indicated by lower branch heights from the baseline condition (Fig 4.4). The WR condition most similar to baseline was the light posterior shank condition. The two WR conditions most dissimilar to baseline were the heavy posterior thigh and heavy anterior thigh conditions.

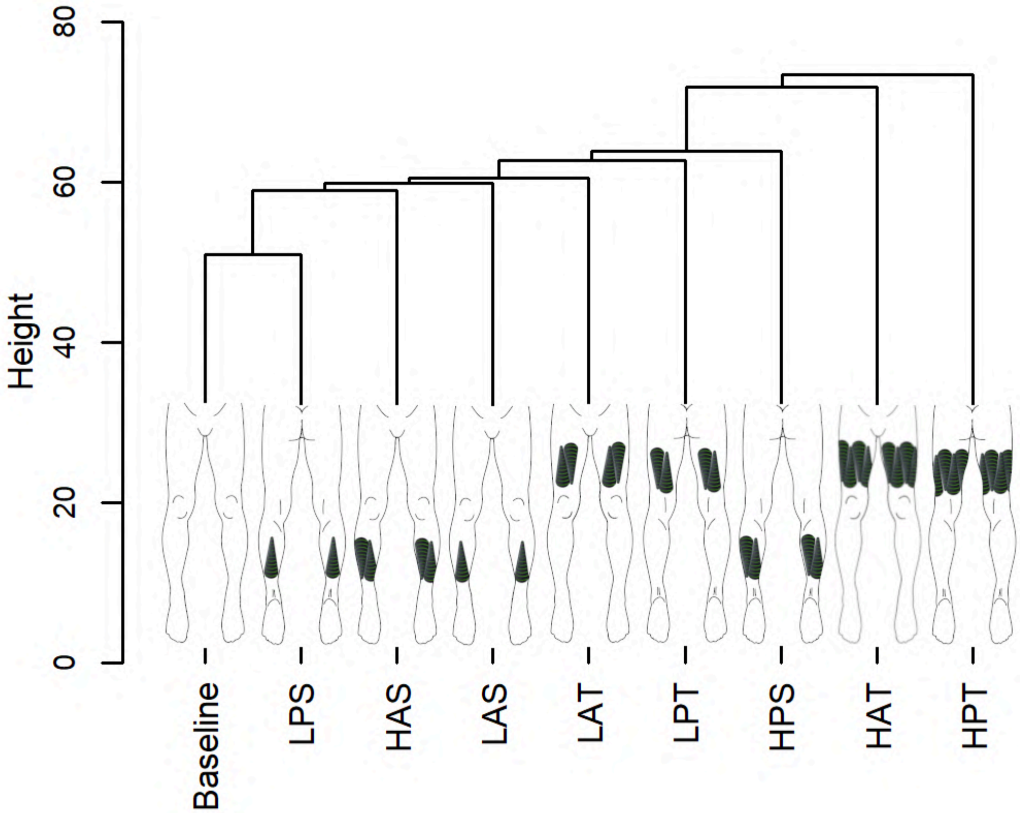

Fig 4.4 Hierarchical cluster analysis of whole body coordination at group-level. The height of branches indicates the degree of dissimilarity between coordination patterns derived from the Euclidean distance measure. Diagrammatic representation of each WR condition is included on the relevant branch. LPS, light posterior shank; HAS, heavy anterior shank; LAS, light anterior shank; LAT, light anterior thigh; LPT, light posterior thigh; HPS, heavy posterior shank; HAT, heavy anterior thigh; HPT, heavy posterior thigh.

Whole body coordination patterns of each individual were clustered together irrespective of the WR condition (Fig 4.5). Differences in coordination patterns between individuals were therefore greater than the changes to individual coordination induced by the addition of WR, highlighting the uniqueness of individual acceleration stride coordination. The extent of coordination dissimilarity induced by WR in general compared with baseline varied across participants. Responses to each WR magnitude and configuration also differed participant-to-participant. P2 demonstrated the most distinct coordination from the group and also exhibited relatively more similar coordination to baseline in the presence of WR in general, as indicated by lower average branch heights across conditions. P2 was the only participant for which the most similar coordination to baseline was expressed in the presence of a heavy WR condition (heavy anterior shank). For P3, coordination in the presence of light shank loading was very similar to baseline, while coordination in the heavy posterior thigh condition was markedly different. The most substantial within-individual deviation of coordination from baseline was shown by P1 in the presence of heavy anterior thigh WR.

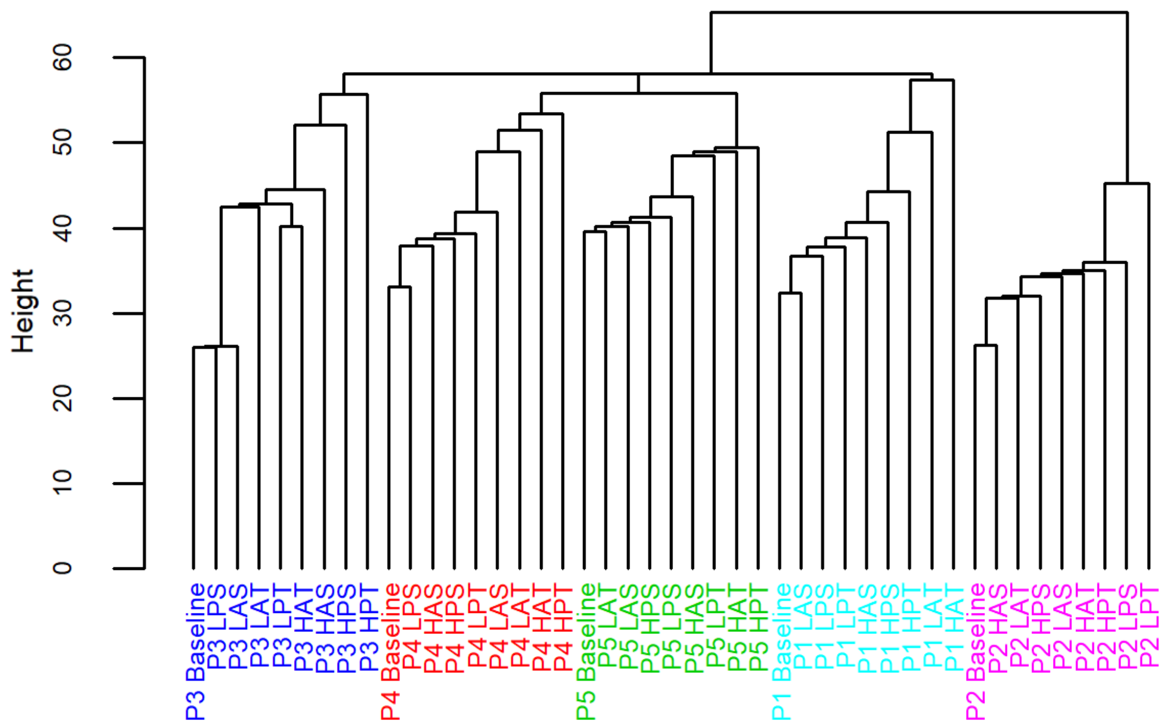

Fig 4.5 Hierarchical cluster analysis of whole body coordination within-individuals. The height of branches indicates the degree of dissimilarity between coordination patterns derived from the Euclidean distance measure. Unique colouring is used in addition to participant initials to distinguish between individuals. LPS, light posterior shank; HAS, heavy anterior shank; LAS, light anterior shank; LAT, light anterior thigh; LPT, light posterior thigh; HPS, heavy posterior shank; HAT, heavy anterior thigh; HPT, heavy posterior thigh.

4.4.3 Self-organising map

Fig 4.6 presents the trained SOM and best-matching unit trajectories for each participant in the two most dissimilar (heavy posterior thigh and heavy anterior thigh) conditions to baseline. Best-matching unit trajectories for each participant in the remaining conditions are provided in Appendix Figure 2.1. While the magnitude of change to coordination brought about by heavy anterior and heavy posterior thigh WR appeared similar in P4 and P5 according to the within-individual hierarchical cluster analysis, the best-matching unit trajectories reveal that the characteristics of the coordinative changes were different with respect to the portion of the stride cycle affected. Looking between each touchdown and toe-off event, the best-matching unit trajectories for each participant can be compared between conditions to understand where in the stride cycle differences manifested. For P4, the entire stride appeared to be affected in the heavy posterior thigh condition, whereas the middle portion of the stride appeared most affected in the heavy anterior thigh condition. For P5, the period between left foot toe-off and right foot toe-off appeared most affected, particularly in the heavy posterior thigh condition. P1 exhibited markedly dissimilar coordination in the heavy anterior thigh condition compared with baseline between first left foot toe-off to right foot toe-off. Lastly, for P3, the end of the stride cycle between left foot touchdown and the second instance of left foot toe-off differed substantially relative to baseline in the heavy posterior thigh condition.

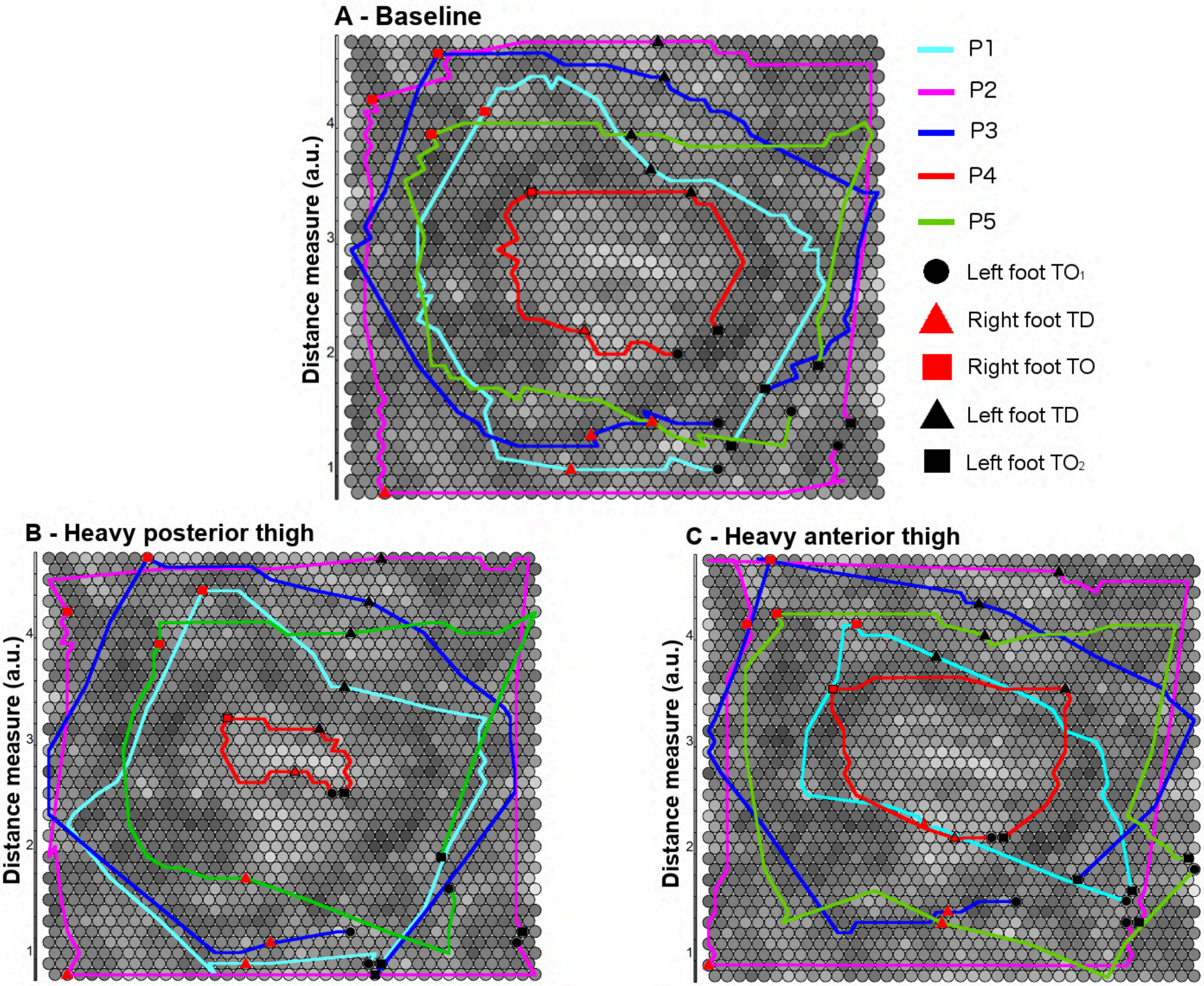

Fig 4.6 Trained SOM and best-matching unit trajectories for each participant. (A) Baseline. (B) Heavy posterior thigh condition. (C) Heavy anterior thigh condition. Shading indicates the distance of each cell to its neighbours with darker shaded areas having a smaller distance. Participants are indicated by unique colours. Shapes and colours are used to indicate key phases of the stride cycle. Black circle, first left foot toe-off (beginning of stride) (TO_1); red triangle, right foot touchdown (TD); red square, right foot toe-off (TO); black triangle, left foot touchdown (TD); black square, second left foot toe-off (end of stride) (TO_2).

4.4.4 Joint-level distance matrix

The results of the distance matrices constructed from time-continuous joint angles between baseline and the two most dissimilar conditions (heavy posterior thigh and heavy anterior thigh) are presented in Appendix Table 2.2. For baseline versus the heavy posterior thigh condition, the five most dissimilar joints and motion planes were the pelvis segment in the sagittal plane, right shoulder in the transverse plane, right and left hips in the sagittal plane, and right shoulder in the sagittal plane. For baseline versus the heavy anterior thigh condition, the five most dissimilar joints and motion planes were the right and left shoulders in the transverse plane, thorax in the sagittal plane, and right and left shoulders in the sagittal plane. Time series ensemble means ± SD for these joints and planes are presented in Fig 4.7. On average, in the heavy posterior thigh condition, pelvic orientation was closer to upright standing and there was greater hip extension throughout the stride cycle on both the left and right side compared with baseline. In the heavy anterior thigh condition, amplitude of movement at the shoulders in the transverse and sagittal planes appeared greater compared with baseline.

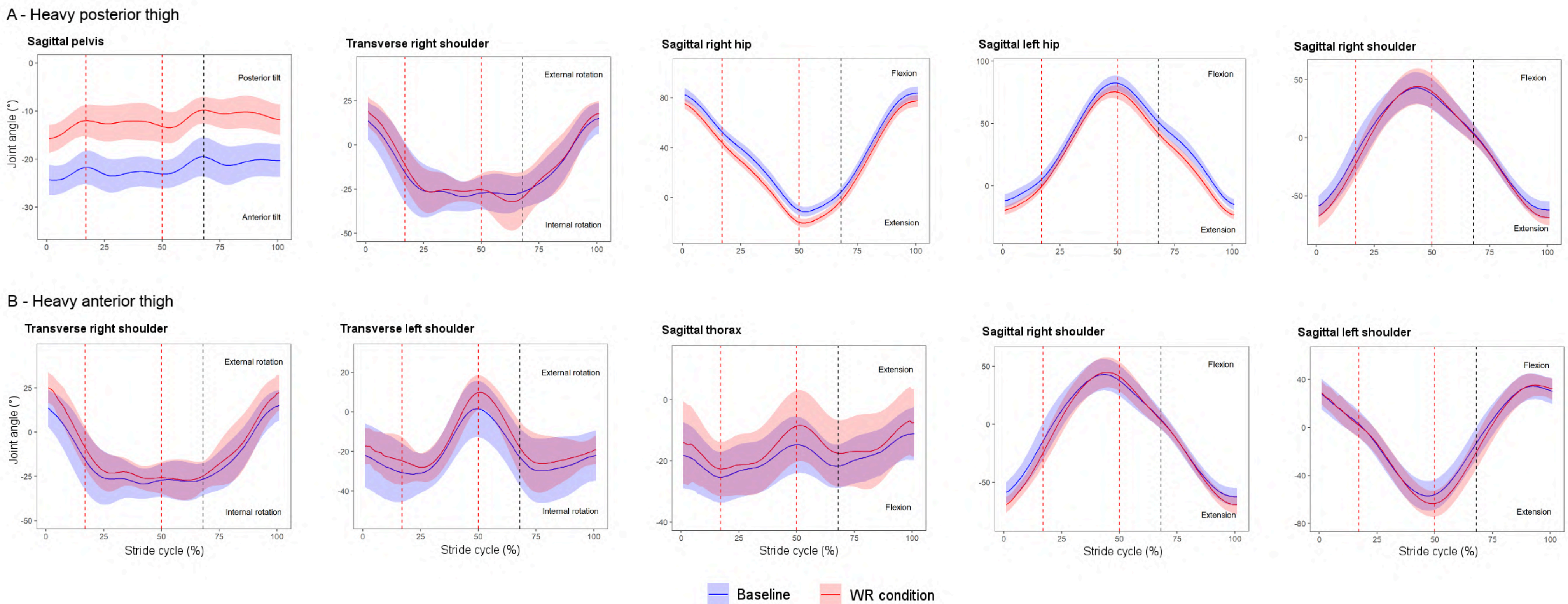

Fig 4.7 Joint angle means ± SD for most dissimilar joints and motion planes throughout stride cycle as indicated by joint-level distance matrix. (A) Baseline versus heavy posterior thigh condition. (B) Baseline versus heavy anterior thigh condition. Dark lines indicate ensemble means and shaded areas indicate SD. Vertical dashed lines represent touchdown and toe-off on the right foot (red) and touchdown on the left foot (black).

4.5 Discussion

4.5.1 Main findings

This study sought to investigate the extent and manner of changes to whole body coordination during early acceleration in response to the addition of various WR loading configurations and magnitudes among five Australian Rules football players. Across the participant group, heavy posterior and anterior thigh WR conditions brought about the most dissimilar coordination patterns compared with baseline. On average, heavy posterior thigh WR loading resulted in a more neutral pelvic position with greater hip extension throughout the stride cycle, while coordination dissimilarity in the presence of heavy anterior thigh loading manifested most in upper body joints, particularly the shoulders in the transverse and sagittal planes. Coordination was most similar to baseline in the light posterior shank WR condition.

The findings offer a starting point for coaches seeking to use WR as a movement control parameter to alter acceleration technique. Coaches wanting to promote greater hip extension or increase the upper body contribution to acceleration among their athletes, for example, may start by exploring posterior and anterior thigh WR, respectively. Alternatively, coaches may use WR to create movement variability generally as a means to encourage autonomous exploration of different coordinative states (Schöllhorn et al. 2012; Button et al. 2005). This can facilitate athlete-driven technique changes and improved performance, particularly if interspersed with unloaded sprints and coupled with knowledge of results (i.e. sprint time) (Brisson and Alain 1996; Davids et al. 1994; Winstein et al. 1994). The findings of this study suggest that exposure to relatively heavier WR loading magnitudes may be more appropriate for this purpose.

Importantly, individual-level analyses, which were included in recognition of ongoing calls for consideration of such data in biomechanics research (Schöllhorn and Bauer 1998; Ball and Best 2012; Glazier and Mehdizadeh 2019), demonstrated that each individual had a clearly distinct coordination pattern. Participants also differed in the extent and manner in which their coordination changed when WR was applied. Although heavy thigh WR conditions tended to alter coordination to a greater extent, this was not uniformly the case. Coaches must keep this in mind when pursuing the use of WR, or any constraint, as a movement control parameter, especially in the context of a team setting.

4.5.2 Comparisons to previous WR research

As a matter of situating this study within existing WR research it is important to note that average acceleration outcome measures (20 m sprint time, 10 m split time, and COM velocity at 4 m) differed minimally based on WR condition across the group. There were also no obvious trends in relation to whole body spatiotemporal measures. While inferential analyses were not performed on these data, similar findings in larger participant cohorts have been reported with lower body WR of comparable magnitudes (Macadam et al. 2017b; Macadam et al. 2020b). Other studies have described decreased stride frequency and increased ground contact time, though the minimal change to early acceleration performance appears consistent (Simperingham et al. 2016; Simperingham et al. 2020). Maintenance of acceleration in the presence of a WR constraint appears to suggest exploitation of movement system degeneracy among the group. The heavy posterior thigh condition, for example, which gave rise to the most dissimilar coordination patterns compared with baseline, only increased 20 m sprint time by 0.04 s on average.

4.5.3 Skill acquisition and coaching implications

For field-based sport athletes, there is a need for acceleration coordination patterns to be adaptable given the vast array of unique scenarios that can emerge from the interactions between task (e.g. evading an opponent), environmental (e.g. slippery playing surface), and organismic (e.g. fatigue) constraints (Davids et al. 2008a; Chow et al. 2016). In practical terms, movement adaptability serves to limit performance outcome variability, and is a hallmark of higher performing athletes across many sports (Chow et al. 2006a; Barris et al. 2014). Increased adaptability may also attenuate injury risk, especially in the context of actions performed repeatedly, by distributing stress across a wider variety of structures (Bartlett et al. 2007; Hamill et al. 2012; Nordin and Dufek 2019). Critically, the capacity for individuals to be adaptable appears to be trainable through exposure to novel constraints, driving exploration of alternate coordination patterns capable of maintaining task performance (Barris et al. 2014; Lee et al. 2014). In this study, the most similar coordination pattern to a baseline condition as indicated by individual-level hierarchical clustering was exhibited by P3 in the light posterior shank condition. Surprisingly, this was also the condition in which the greatest average increase in 20 m sprint time occurred (+0.17 s from baseline). In this instance, the WR may have been an insufficient perturbation to move the participant away from their stable baseline coordination and/or the participant may not have perceived a diminution in acceleration so did not seek an alternate movement strategy to maintain task performance (Glazier 2021). This is therefore likely a less effective loading configuration and magnitude for training movement adaptability in this individual. In contrast, the most dissimilar coordination pattern to a baseline condition was exhibited by P1 in the heavy anterior thigh condition, and was accompanied by only a slight increase in 20 m sprint time (+0.05 s from baseline). This suggests a suitable challenge to sprint adaptability for this individual. Training studies with pre- and post-training coordination variability assessments are needed, however, to make definitive, generalisable conclusions in this respect. On the matter of movement variability, trial-level hierarchical clustering may also be worth considering as a means of evaluating whole body coordination stability on a trial-to-trial basis within-individuals and conditions. For a given individual, whole body coordination with a given WR configuration may be similar to baseline on average, but relatively less stable between trials, suggesting a coordinative challenge.

Despite subtle within-individual differences, participants generally exhibited the most dissimilar coordination in heavy thigh WR conditions compared with baseline sprints. P2 was a notable exception to this trend, however, showing no clear pattern in the responses to WR. This participant also had the most distinct coordination and slowest 20 m sprint times, suggesting that sprint acceleration skill level may have been lower than other participants. Athlete skill level is yet another practical consideration for coaches. Lesser skilled individuals often have higher coordination variability generally (Wilson et al. 2008). This could explain the less predictable responses to WR in P2. For such individuals, repetitive practice with minimal alteration to constraints may be preferable (Davids et al. 2008b).

WR may be a suitable constraint to channel coordination patterns toward organisational states deemed favourable for performance (Simperingham et al. 2015; Macadam et al. 2019a). Among this participant group, heavy thigh WR loading effected the greatest change in whole body coordination compared with baseline acceleration. It is not obvious why heavy thigh loading brought about greater changes than heavy shank loading, though it may have been due to the greater system load in the former condition. This difference was a necessary consequence of the decision to match thigh and shank loads on the basis of changes to the moment of inertia about the hip throughout the acceleration stride. For the heavy posterior thigh condition, coordination shifted towards the adoption of greater hip extension throughout the stride and a more neutral pelvic position. The tendency toward greater hip extension may have been an effect of the posterior shift in mass of the thigh segments. Pelvic position in the heavy posterior thigh condition may have changed to maintain the preferred relationship between the global centre of mass and the posteriorly-shifted base of support arising from greater peak hip extension (Hof 2008). Given the importance of hip extension for propulsion during acceleration, posterior thigh WR has potential as a coaching tool to accentuate this motion among athletes for whom this is identified as a technical shortcoming (Morin et al. 2015; Haugen et al. 2018). Future research should focus specifically on the effect of this loading scheme on sagittal plane pelvis and hip kinematics among a larger athlete sample to verify the generalisability of such a prescription. In terms of heavy anterior thigh WR, movement amplitude at the shoulders appeared to increase on average in both the sagittal and transverse planes. Though the role of arms during in acceleration is debated (Macadam et al. 2018), there is clearly high movement coupling between each shoulder and contralateral hip joint (Slawinski et al. 2013). With heavy anterior thigh WR loading, the increased arm angular displacement may have acted to preserve proportionality between the relative rotational work performed at the shoulders and hips (Slawinski et al. 2010; Macadam et al. 2021a). Heavy anterior thigh WR could therefore serve as a constraint to promote arm swing action during acceleration, though consideration must be afforded to whether a given athlete is likely to benefit from accentuated movement in both the sagittal and transverse planes.

4.5.4 Limitations

As addressed throughout, a limitation of this study is the small sample size. This type of exploratory study does, however, offer starting points for coaches working in applied settings and important signposts for future investigations. It should also be reiterated that the findings pertain only to a specific portion of early sprint acceleration (steps 3 and 4) and that the effects of WR likely differ in other phases of sprinting, such as at maximum velocity. Worth noting also is that complex systems-based pedagogical approaches emphasise ecological validity in training. Ideally, this would extend to the testing environment also, though the acquisition of detailed kinematic data in on-field settings poses challenges. Lastly, individuals may have naturally exhibited small improvements in sprint acceleration performance over the testing period as a function of high frequency sprint exposures during match play over the course of their competitive season (Caldwell and Peters 2009; Evangelos et al. 2016).

4.6 Conclusions

Across the participant group, heavy WR applied to the thighs had the greatest effect on whole body coordination during sprint acceleration. On average, heavy posterior thigh WR led to altered pelvic position and greater hip extension, while heavy anterior thigh WR led to accentuated movement at the shoulders in the transverse and sagittal planes. Future research may investigate these specific effects in a larger sample group to determine the generalisability of findings. Given the absence of other research into the changes to whole body coordination induced by WR, heavy thigh WR may be an appropriate starting point for coaches seeking to use WR as a movement control parameter or as a tool to promote movement variability in acceleration for field-based sport athletes. Coaches should note, however, that individuals did exhibit variation in the extent and manner in which each WR condition altered coordination, which may have been the result of differences in individual coordination dynamics and/or skill level.

Chapter 5 – Effects of anterior and posterior thigh wearable resistance on sprint kinetics and kinematics during late acceleration

5.1 Abstract

Lightweight wearable resistance can be used to impact a variety of neuromuscular and technical factors involved in the late acceleration phase of sprinting. Understanding the directionality of such changes can inform strength and conditioning coaches seeking to use wearable resistance as a training intervention to improve sprint acceleration among field-based athletes. Five semi-professional male Australian Rules football players undertook maximal 20 m sprints with either no wearable resistance, anterior thigh, or posterior thigh wearable resistance. Whole body spatiotemporal and kinetic measures, and sagittal plane hip joint kinetic and kinematic measures were collected during the late acceleration phase of each sprint. Addition of anterior and posterior thigh wearable resistance decreased acceleration performance in most participants. There was generally also less demand on hip flexion, based on average hip flexion moment, with wearable resistance. Peak propulsive force and propulsive impulse was accentuated by wearable resistance in most participants, particularly with an anterior thigh configuration. Hip joint absolute rotational work during hip extension was greatest with addition of posterior thigh wearable resistance. Neither wearable resistance configuration had a notable effect on acceleration technique in relation to actions of the thighs in front of the body i.e. a "front-side mechanics" technical model of sprinting. Also worth noting was substantial variation in the effects of wearable resistance configuration on kinetic and kinematic variables between individuals. The findings indicate parameters that may be emphasised or "overloaded" by addition of wearable resistance with possible implications for training and coaching, as well as variables worthy of further investigation in larger cohort or training studies.

5.2 Introduction

Acceleration efforts in field-based sports such as soccer, Australian Rules football, and rugby union typically occur over 10-20 m, involve increasing running speed, and last for less than 10 s (Spencer et al. 2005; Kawamori et al. 2013). Despite short distances and durations, these efforts are often associated with critical match events such as winning a contested ball or reaching open space before an opponent (Reilly et al. 2000a; Rienzi et al. 2000). As such, enhancing athlete acceleration performance is a pivotal objective for strength and conditioning coaches working in these sports.

Acceleration performance is influenced by both neuromuscular and technical factors (Buchheit et al. 2014). For example, the capacity of lower body muscles to generate force allows for greater impulse production during ground contact, while segment orientation (considered a technical factor (Debaere et al. 2013)) influences the extent to which this occurs in a horizontal direction (Morin et al. 2011). Training interventions aimed at altering specific biomechanical factors are usually evaluated on the basis of their impact on performance and the factors in question (Keiner et al. 2014; Balsalobre-Fernandez et al. 2013; Blazevich and Jenkins 2002; Bezodis et al. 2015). For example, in Morin et al.'s (Morin et al. 2017) investigation into heavy resisted sprint training, positive impacts on acceleration performance were attributed to improvements in theoretical maximal force production and the ratio of propulsive ground reaction force (GRF) to total GRF. However, these process variable changes would have occurred interdependently with changes in technical factors, such as segment orientation, which themselves are likely to have also impacted performance (Haugen et al. 2019).

Consequently, approaching sprint acceleration performance from a complex systems perspective, where effects of a training intervention on a range of process measures are considered, may provide coaches with a more comprehensive understanding of an intervention's effects (Davids et al. 2006a; Davids et al. 2014; Komar et al. 2015; Wild and Goodwin 2023). In practice, this often requires implementation of multivariate and multidimensional analyses of several variables. Applying a complex systems perspective to evaluating interventions also aligns with the growing popularity of complex systems-based pedagogical approaches in strength and conditioning (Wild and Goodwin 2023; Nimphius

2017), which have emerged in favour of skill deconstruction and part practice methods (Verhoeff et al. 2020).

Lightweight wearable resistance (WR) is a training intervention receiving growing attention due to its potential to impact a variety of factors related to acceleration performance (Macadam et al. 2017b; Simperingham et al. 2020; Feser et al. 2021b). Application of WR on body segments during athletic movements can increase demand on the neuromuscular system (Hurst et al. 2020; Bustos et al. 2020; Feser et al. 2021b), while also acting as a constraint to direct emergent movements, which may be exploited for technique alteration (Trounson et al. 2020). To date, investigations into WR have tended to employ discrete analyses of factors contributing to acceleration performance and possibly underemphasised their potential interdependence (Macadam et al. 2017b; Uthoff et al. 2020; Macadam et al. 2020b). This appears to have contributed in part to ambiguity about what influence WR may have on neuromuscular qualities and technical factors. For example, in several instances, reductions in sprint-derived metrics are seen as being indicative of "overload" brought about by WR, e.g. step frequency (Macadam et al. 2019a; Simperingham et al. 2020; Hurst et al. 2020), vertical stiffness (Macadam et al. 2017b), and joint angular velocities (Feser et al. 2023). In other studies, however, *increases* in metrics are described as instances of "overload", e.g. vertical GRF (Macadam et al. 2019a) or vertical impulse (Uthoff et al. 2020).

This presents ambiguity for coaches seeking to use WR as a training intervention. A recent investigation beyond whole body spatiotemporal and kinetic parameters ultimately clarified that the neuromuscular demands of WR primarily manifested in increased mean rotational energy at the joint proximal to loading (Macadam et al. 2021a). These joint-level kinetic metrics could be explored further, however, to provide even greater clarity about the "overload" effect of WR. Further examination into the emergent movement tendencies resulting from WR application also has implications for its use in complex systems-based pedagogical frameworks, where technical changes may be facilitated through movement exploration and self-organisation without explicit instruction.

This study aims to investigate both of these areas; specifically considering the effects of anterior and posterior thigh WR on spatiotemporal parameters, whole body kinetics, sagittal plane joint-based kinematics and kinetics, and the popular "front-side mechanics" technical model of sprinting during late acceleration (Mann and Murphy 2015; Mendiguchia et al. 2021). Findings will enrich coaches' understanding of the possible impacts of WR on acceleration neuromuscular and technical elements, while continuing to promote an appreciation for the interplay between factors contributing to acceleration and the multifaceted effects of training interventions.

5.3 Materials and methods

5.3.1 Participants

Five semi-professional male Australian Rules football players (mean ± SD; age: 21.2 ± 4.1 years; height: 180.6 ± 6.5 cm; body mass: 72 ± 4.3 kg) were recruited between July 30 and October 15 2019 for participation in this study. Participants are hereafter denoted as P1-P5. Participants had no prior experience with WR. All provided written informed consent and were free from musculoskeletal injury at the time of, and in the 6 months prior to, testing. All procedures used in this study complied with the criteria of the declaration of Helsinki and the ethical approval granted by the Victoria University Human Research Ethics Committee.

5.3.2 Procedure

5.3.2.1 Study design

Testing was undertaken in the Biomechanics Laboratory at Victoria University, Footscray Park, Melbourne, Australia. Participants attended the laboratory on three occasions in total, comprising one baseline testing session and two WR testing sessions. Each testing session was separated by at least 1 week. During testing sessions, participants performed three maximal 20 m sprints commencing from a stationary position, interspersed with 3 min rest periods. In the baseline testing session, participants performed all sprints without addition of WR. During WR testing sessions, participants performed sprints with WR applied to either the anterior or posterior aspect of the thighs. The order of WR testing sessions was randomised between participants. In each sprint whole body spatiotemporal and kinetic measures, and joint kinematics and kinetics were captured at the 16 m mark to examine the effects of WR on these variables during the late acceleration phase of sprinting (Hunter et al. 2005).

5.3.2.2 Experimental setup

A 20 m section of the Biomechanics Laboratory with a Mondo track surface defined the sprint area. Infrared timing gates (Smart Speed, Fusion Sport, Brisbane, Australia) were situated at the 0 and 20 m marks along the sprint area. For each sprint, participants adopted a self-selected 2-point upright starting stance with the front foot 0.9 m behind the starting line. Two recessed force plates (an AMTI LG6-4 and an AMTI OR6-5-1, Advanced Medical Technologies, Inc., Watertown, MA) located 16 m from the sprint start line and sampling at 1000 Hz were used to obtain whole body kinetic measures. Motion analysis cameras were arranged around the 16 m mark and the approximate capture volume was 5.0 m long, 2.5 m high, and 3.0 m, wide. A 10-camera Vicon motion analysis system (T-40 series, Vicon Nexus v2, Oxford, UK) sampling at 250 Hz was used for collection of whole body spatiotemporal and joint kinematic and kinetic data. A total of 36 reflective markers with 12.7 mm diameter were attached to lower body landmarks on the pelvis, thighs, shanks, and feet according to the Plug-In-Gait model (Plug-In-Gait Marker Set, Vicon, Oxford, UK). In Vicon Nexus software, a global reference system was defined with the positive Y-axis horizontal in the direction of the sprints, the positive X-axis perpendicular to the Y-axis – horizontal in the right direction – and the positive Z-axis in the vertical direction.

5.3.2.3 Wearable resistance

Throughout all testing sessions, participants wore Lila™ Exogen™ (Sportboleh Sdh Bhd, Kuala Lumpur, Malaysia) compression shorts. During WR testing sessions, a combination of 50, 100, and 200 g fusiform shaped loads (with Velcro backing) totalling the required loading magnitude were attached to the compression garments (Fig 5.1). Two WR configurations were investigated – anterior thigh and posterior thigh. WR magnitude corresponded to an increase of 6% in the moment of inertia about the hip throughout an acceleration stride in accordance with sagittal plane lower limb motion previously observed during acceleration (Debaere et al. 2013). Participant height and weight was used to determine the specific WR magnitudes required at the thigh to satisfy these conditions based on Plagenhoef's (Plagenhoef et al. 1983) estimations of segment parameters. Table 5.1 provides the WR loading magnitudes for each participant. Fusiform loads were added in an alternating fashion between a proximal-dominant and distal-dominant orientation. The smallest number of possible loads to achieve the required loading magnitude was used.

Fig 5.1 Lila™ Exogen™ compression shorts with posterior thigh loading.

Table 5.1 Wearable resistance loading magnitudes for participants based on individual anthropometrics.

Participant	Height (m)	Weight (kg)	WR magnitude (g per leg)
P1	1.7	70	550
P2	1.86	79	600
P3	1.8	70	550
P4	1.81	73	550
P5	1.86	68	500

5.3.2.4 Data collection

Following application of compression garments and attachment of reflective markers, participants undertook an initial warm-up, which consisted of a series of dynamic mobility drills followed by three sub-maximal 20 m sprints, and one maximal effort 20 m sprint. Participants then performed three recorded maximal 20 m sprints, each separated by 3 mins rest. The only instruction provided to participants was to sprint as fast as possible. In WR testing sessions, researchers applied the requisite WR loads to the participant during the rest period between the final warm-up sprint and the first recorded sprint, and the WR was left on for remaining sprints.

5.3.3 Data processing

Raw marker data were labelled in Vicon Nexus with spline filling used in instances of marker drop out (to an upper limit of 10 consecutive frames). Marker data were then transferred to Visual 3D software (C-motion, Rockville, MD, USA) for calculation of whole body spatiotemporal and kinetic measures, and joint kinematics and kinetics, starting with the following steps. Marker trajectories were smoothed via a fourth order low-pass Butterworth filter with 10 Hz cut-off frequency, based on mean results of residual analyses (Winter 2009). A seven segment model (pelvis, thighs, shanks, and feet) was constructed for each participant. Each sprint was trimmed to one step, which was defined as the period between two consecutive toe-off events on contralateral limbs. Toe-off was defined by the initial rise in vertical displacement of the toe marker proceeding its lowest point at the end of stance (Schache et al. 2001; Nagahara and Zushi 2013). The step in which the second toe off occurred closest to the 16 m mark was selected for analysis in each instance. Of the 45 trials captured, there were five in which no complete step occurred on the force plates, meaning whole body kinetic measures were not obtained from these trials.

5.3.3.1 Whole body spatiotemporal measures

Using the model created for each participant in Visual 3D, an in-built model based function was used to calculate mean model centre of mass (COM) velocity in the Y-axis across the step. Flight time was defined as the point of take-off from one foot to the point of ground contact on the contralateral foot. Ground contact time was defined as the point of initial ground contact until the point of take-off on the same foot (Mero and Komi 1985). Step length was defined as the horizontal distance between successive toe-off events of each contralateral foot (Decker et al. 2013). Step frequency was defined as the number of steps taken per second and was calculated as the inverse of step duration (sum of flight time and ground contact time) (Macadam et al. 2020b).

5.3.3.2 Whole body kinetic measures

For whole body kinetic measures, force plate data were first smoothed via a fourth order low-pass Butterworth filter with 100 Hz cut-off frequency. Peak vertical force was determined from the peak force in the vertical Z-axis. Peak braking and propulsive forces were determined from the peak force in the negative and positive Y-axis, respectively. Braking and propulsive impulse were determined from the integral of the force-time curve in the negative and positive Y-axis, respectively. Absolute data are reported in each instance given differences in participant weight between baseline and WR trials.

5.3.3.3 Joint kinematics and kinetics

Prior to calculation of joint kinematics and kinetics, two additional models were created for each participant – one for each WR condition. Using thigh length and the radii at proximal (hip) and distal (knee) ends obtained from Visual 3D, the thigh segment in isolation was modelled for each participant in MATLAB (v9.14, MathWorks, Natick, MA, USA). The segment's geometric inclination was represented as an angle (α). This angle was derived from the difference in radii between the hip and knee, relative to the thigh's length, following the formula: $\alpha = \arctan\left(\frac{R_{hip}-R_{knee}}{Length_{thigh}}\right)$, where R_{hip} and R_{knee} represent the radii at the hip and knee, respectively. WR was then modelled as a semicircular prism characterised by its height (0.2 m), width (participant-dependent), depth (0.01 m), and weight (participant-dependent). The axial position of the COM of the WR was a fraction (0.5) of the thigh length. The anterior-posterior position of the WR was calculated through linear interpolation between the proximal and distal radii, considering the specified axial position (Fig 5.2). Using thigh COM position obtained from Visual 3D and the COM position of the modelled WR, a new COM position for the combined thigh and WR system was calculated. Inertial properties of the thigh and WR were then also combined according to the parallel axis theorem, to give new inertial properties of the thigh-WR system (Winter 2009). This process was repeated for each participant. In visual 3D, thigh segment properties of models for each participant were then manually adjusted according to the new segment mass, COM and inertial values. Each participant therefore had three models, one corresponding to baseline with no adjustments made to the thigh segments, one for the anterior thigh testing condition and one for the posterior thigh testing condition. For the posterior thigh condition, COM of the combined segments in the anterior-posterior axis was negated relative to the anterior thigh condition. Each model was subsequently used in the corresponding trials for model based calculations of sagittal plane joint kinetics. Model based calculations were performed between the pelvis and thigh segments' local coordinate systems, with the pelvis serving as the reference segment. Hip joint angular velocity, moment, and power in the sagittal plane were calculated on both the flexing and extending hips across the recorded step. All data were normalised to 101 data points (0-100% of the step). Hip joint power data were integrated over time to calculate absolute rotational work (sum of positive and negative work) at the hip in the flexing and extending limbs. In each trial, the distal position of each thigh in relation to the pelvis COM was also calculated across the step and normalised to 101 data points for determination of participant expression of "front-side mechanics".

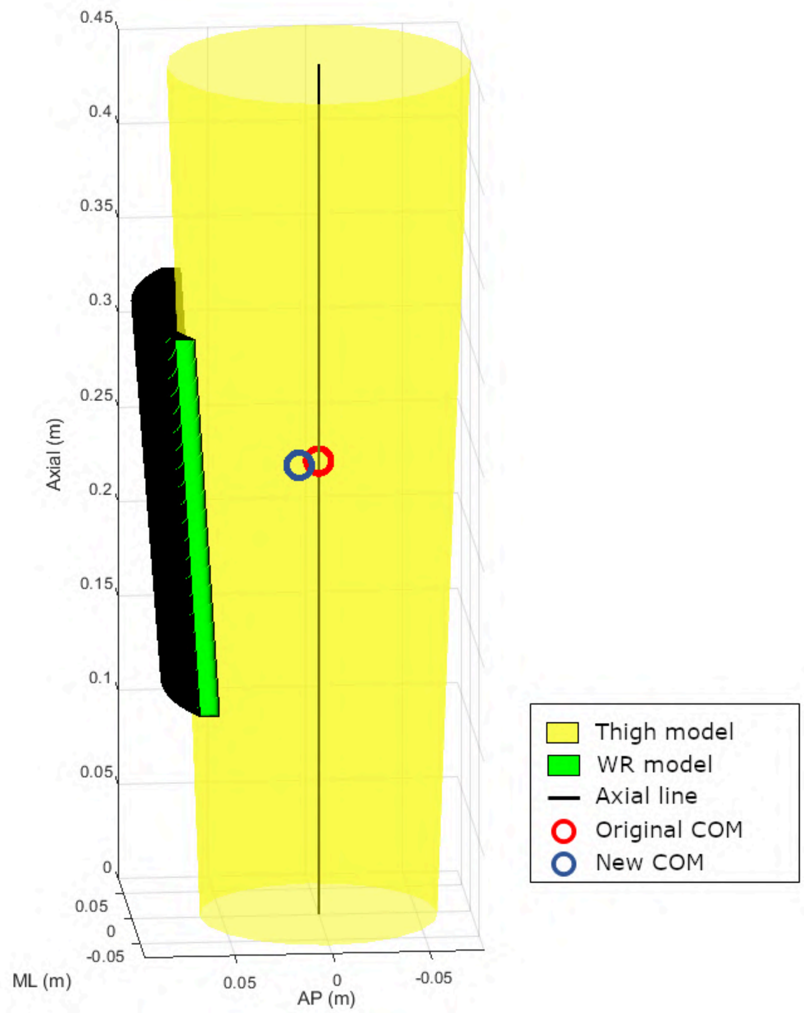

Fig 5.2. Model of thigh with anteriorly positioned WR and associated change in segment COM.

WR, wearable resistance; COM, centre of mass; ML, medial-lateral axis; AP, anterior-posterior axis.

5.3.4 Data analysis

5.3.4.1 Descriptive statistics

Mean, standard deviation, and percentage difference of whole body spatiotemporal and kinetic measures between baseline and WR testing sessions were calculated across the group. Within-individual and group-based ensemble means of continuous hip joint angular velocity, moment, and power were calculated for the flexing and extending hips. Mean and standard

deviation of mean hip joint angular velocity, moment, power, and absolute rotational work across the phases of hip flexion and hip extension were calculated across the group.
The proportion of the step in which the thigh COM on the flexing limb was in front of the pelvis COM was determined in each sprint. This was repeated for the extending limb. Mean proportions for the flexing and extending limbs were calculated in each condition for each participant and across the group.

5.3.4.2 Statistical analysis

For individual-level responses to WR conditions, mean changes from baseline for each parameter were calculated across sprints. Smallest worthwhile change was calculated as 0.2 x baseline standard deviation of a given parameter across the group.

5.3.4.3 Principal component analysis

To investigate shared variation between measured variables, principal component analysis (PCA) was employed. Whole body spatiotemporal measures, whole body kinetic measures, and discrete joint-level kinematic and kinetic measures were scaled in R (version 2023.09.1+494). PCA was performed using the ‘prcomp’ function. Loadings of components were examined to understand the contribution of variables to selected components. Sprint trials were subsequently plotted along the first two principal components and K-means clustering was applied to trials on the basis of each principal component score. Four clusters were chosen to investigate trial grouping patterns based on visual inspection of trial distribution and four naturally occurring ‘quadrants’ defined by the two principal components, suggestive of distinct sprint styles.

5.4 Results

5.4.1 Whole body spatiotemporal measures

Means, standard deviations, and percentage differences of whole body spatiotemporal measures across the group are displayed in Table 5.2. Individual-level mean differences from baseline and smallest worthwhile changes of whole body spatiotemporal measures across conditions for each participant are presented in Fig 5.3.

Table 5.2 Mean ± SD of whole body spatiotemporal measures with percentage change from baseline.

	Baseline	Anterior thigh WR	Posterior thigh WR
COM mean velocity (m.s^{-1})	7.67 ± 0.33	7.53 ± 0.22 (-1.84%)	7.56 ± 0.38 (-1.44%)
Flight time (ms)	110 ± 11	107 ± 8 (-2.76%)	104 ± 9 (-5.61%)
Ground contact time (ms)	122 ± 16	130 ± 16 (+6.35%)	126 ± 17 (+3.32%)
Step length (m)	1.84 ± 0.11	1.83 ± 0.11 (-0.54%)	1.80 ± 0.13 (-2.2%)
Step frequency (Hz)	4.32 ± 0.25	4.24 ± 0.26 (-1.87%)	4.36 ± 0.32 (+0.92%)

WR, wearable resistance; COM, centre of mass.

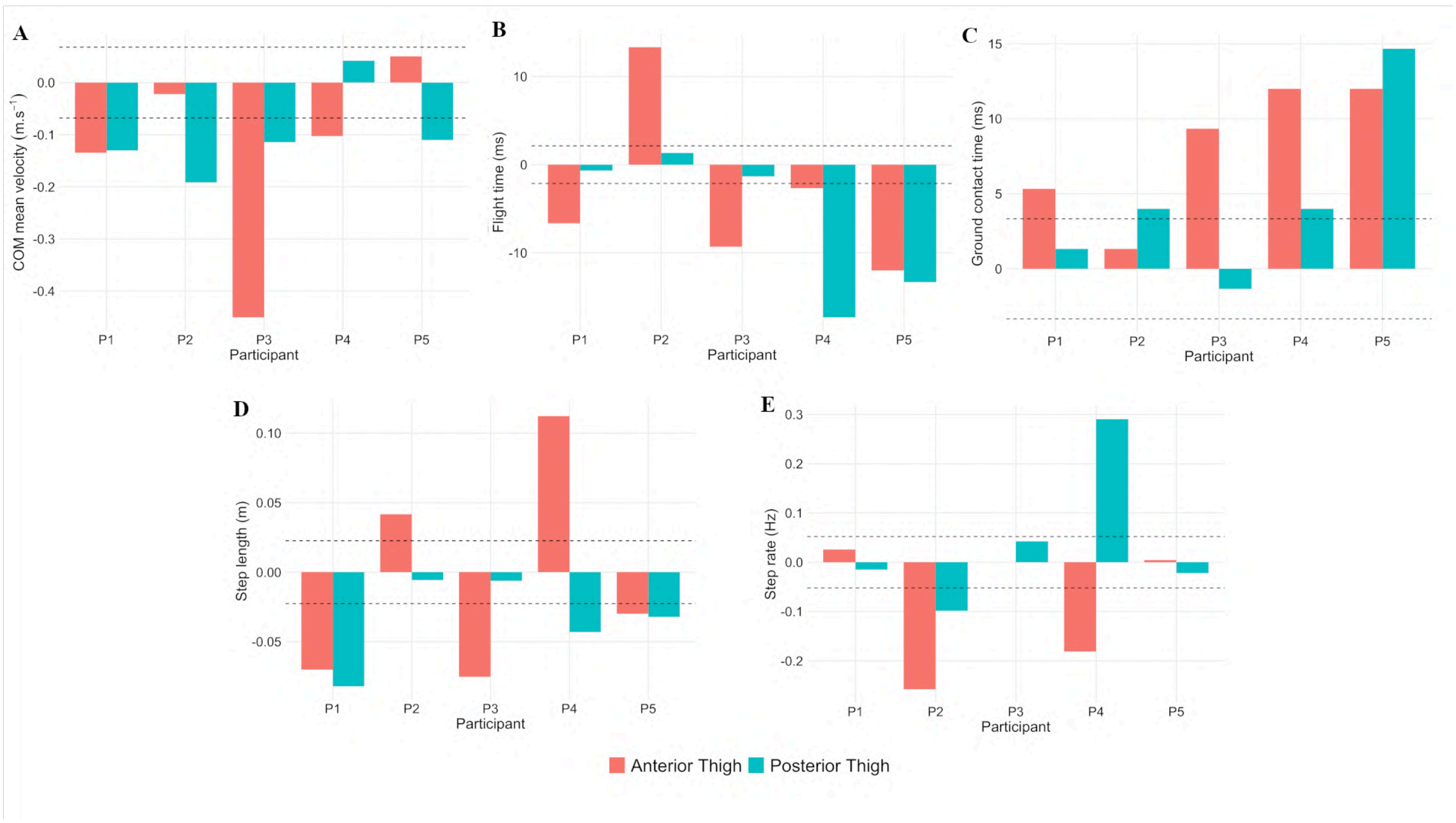

Fig 5.3 Participant-level mean changes in whole body spatiotemporal measures with anterior thigh and posterior thigh WR. (A) Mean change in COM mean velocity from baseline. (B) Mean change in flight time from baseline. (C) Mean change in flight time from baseline. (D) Mean change in step length from baseline. (E) Mean change in step rate from

baseline. Dashed lines indicate the smallest worthwhile change threshold (± 0.20 x baseline condition group-level standard deviation).

5.4.2 Whole body kinetic measures

Means, standard deviations, and percentage differences of whole body kinetic measures across the group are displayed in Table 5.3. Individual-level mean differences from baseline and smallest worthwhile changes of whole body kinetic measures across conditions for each participant are presented in Fig 5.4.

Table 5.3 Mean ± SD of whole body kinetic measures with percentage change from baseline.

	Baseline	Anterior thigh WR	Posterior thigh WR
Peak vertical force (N)	1949.9 ± 125.3	2077.1 ± 270.4 (+6.32%)	2100.5 ± 309.3 (+7.44%)
Peak braking force (N)	618.4 ± 130.1	655.7 ± 184.8 (+5.86%)	665.4 ± 136.6 (+7.32%)
Peak propulsive force (N)	449.1 ± 39.5	482.5 ± 32.6 (+7.17%)	440.5 ± 34.3 (-1.93%)
Braking impulse (N·s)	9.6 ± 2.9	9.9 ± 2.5 (+3.08%)	10.4 ± 2.8 (+8%)
Propulsive impulse (N·s)	20.7 ± 2.5	23.1 ± 1.8 (+11%)	22.1 ± 2. 2 (+6.54%)

WR, wearable resistance.

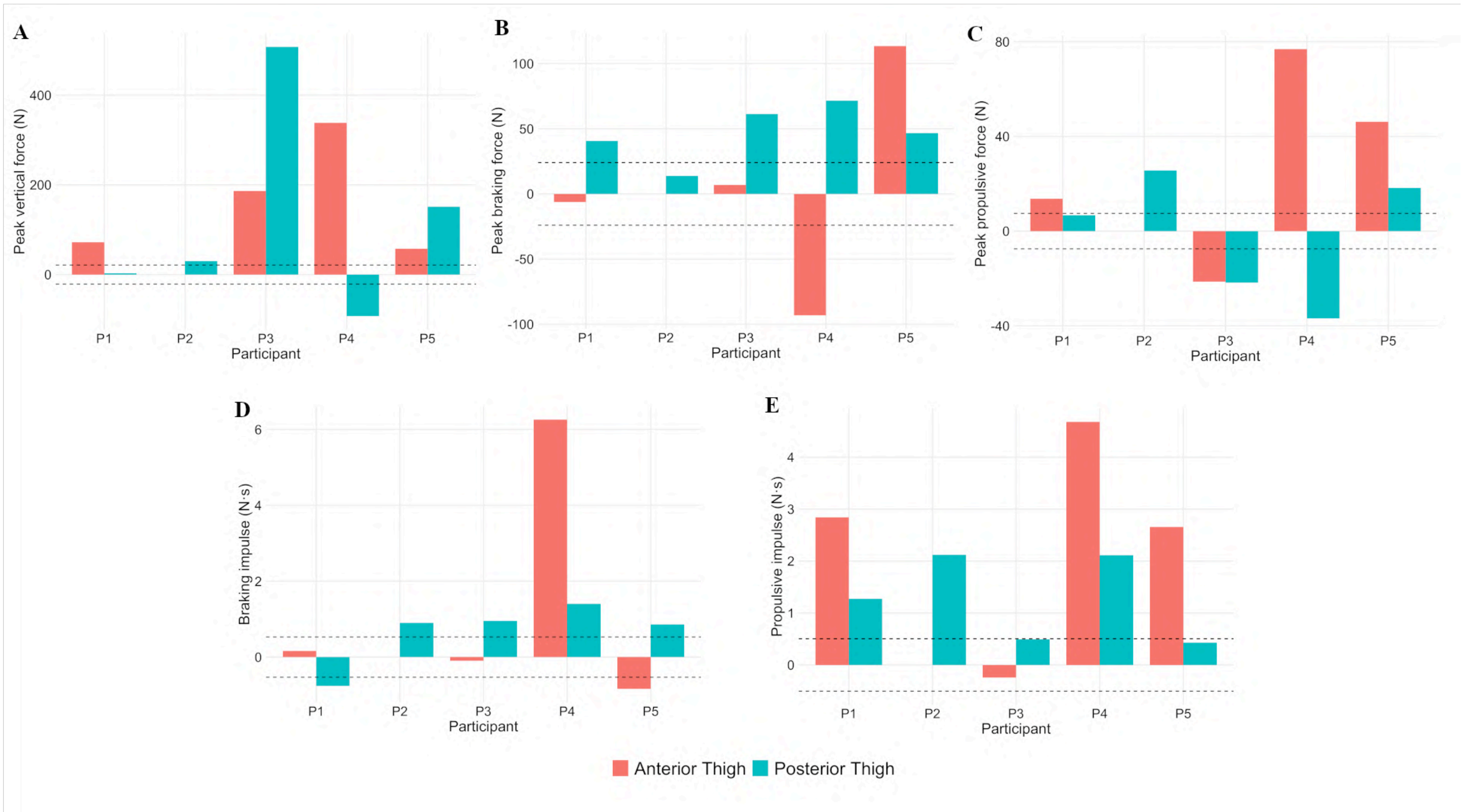

Fig 5.4 Participant-level mean changes in whole body kinetic measures with anterior thigh and posterior thigh WR. (A) Mean change in peak vertical force from baseline. (B) Mean change in peak braking force from baseline. (C) Mean change in peak propulsive force from baseline. (D) Mean change in braking impulse from baseline. (E) Mean change in propulsive impulse from baseline. Dashed lines indicate the smallest worthwhile change threshold (± 0.20 x baseline condition group-level standard deviation).

5.4.3 Joint kinematics and kinetics

Within-individual and group-level ensemble means of hip joint flexion and extension angular velocity, moment, and power in each testing condition are displayed in Appendix Figure 3.1 Appendix Figure 3.2, and Appendix Figure 3.3, respectively.

Means and standard deviations of mean hip joint angular velocity, moment, power, and rotational work across the phases of hip flexion and hip extension across the group are displayed in Table 5.4. Individual-level mean differences from baseline and smallest worthwhile changes of mean hip joint angular velocity, moment, power, and rotational across conditions for each participant are presented in Fig 5.5.

Table 5.4 Mean ± SD of mean hip joint kinematic and kinetic measures across hip flexion and hip extension.

	Baseline	Anterior thigh WR	Posterior thigh WR
Hip flexion angular velocity (°/s)	431.4 ± 33	436.7 ± 34.5	427 ± 27.8
Hip extension angular velocity (°/s)	-401.4 ± 39.4	-392.2 ± 59	-403.7 ± 41.7
Hip flexion moment (N·m)	69.5 ± 13.7	62.3 ± 13.4	61.3 ± 12.7
Hip extension moment (N·m)	-64.6 ± 56.1	-72.2 ± 42.3	-74 ± 48.6
Hip flexion power (W)	424 ± 110.6	398 ± 113.3	384.8 ± 90.7
Hip extension power (W)	376.2 ± 448.3	539.5 ± 328.9	523.8 ± 356.7
Hip flexion absolute rotational work (J)	137.6 ± 22.3	140.1 ± 8.3	145 ± 25.9
Hip extension absolute rotational work (J)	265.6 ± 65.4	237 ± 29.5	284.8 ± 33

WR, wearable resistance.

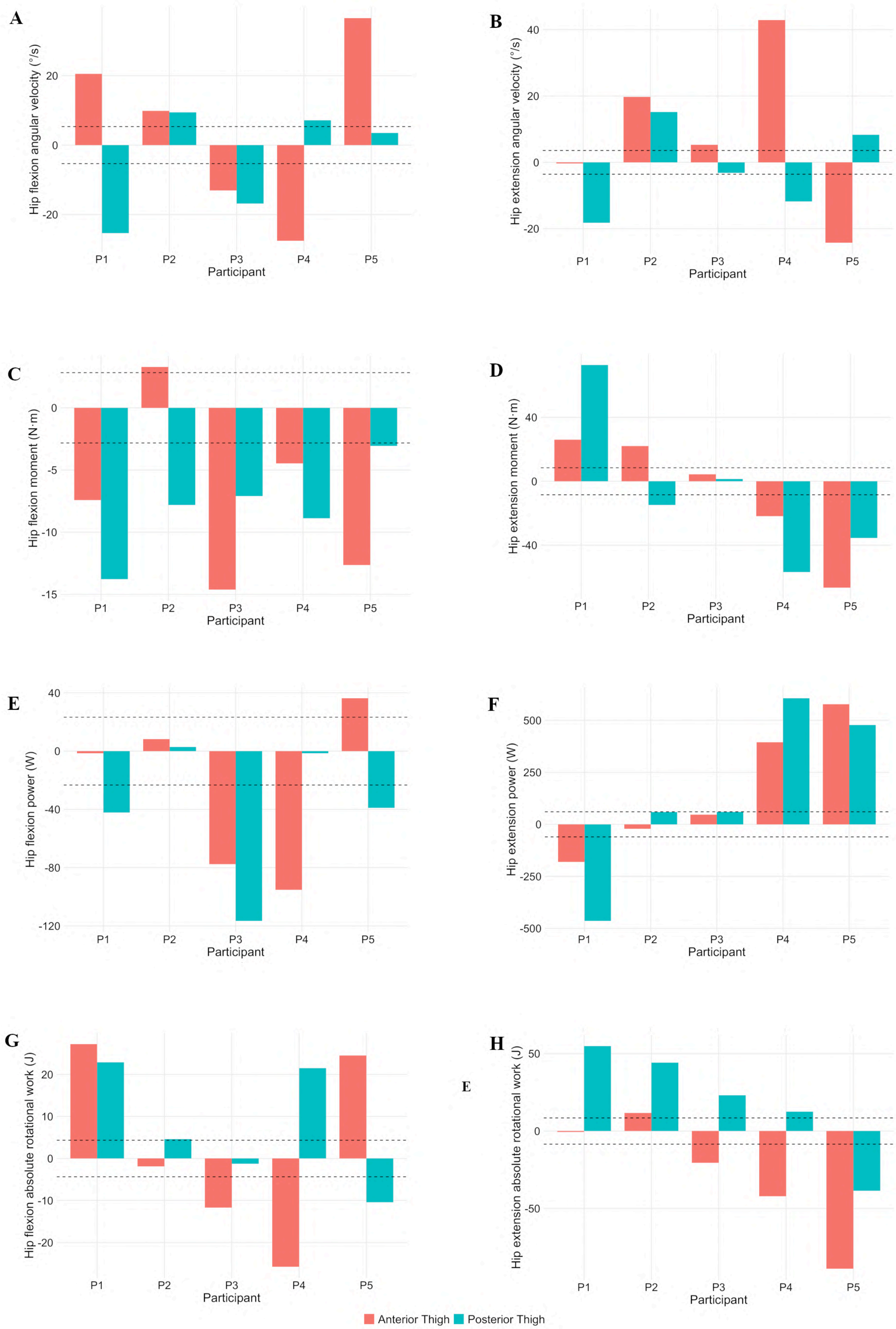

Fig 5.5 Participant-level mean changes in joint kinematic and kinetic measures with

anterior thigh and posterior thigh WR. (A) Mean change in hip flexion angular velocity from baseline. (B) Mean change in hip extension angular velocity from baseline. (C) Mean change in hip flexion moment from baseline. (D) Mean change in hip extension moment from baseline. (E) Mean change in hip flexion power from baseline. (F) Mean change in hip extension power from baseline. (G) Mean change in hip flexion absolute rotational work from baseline. (H) Mean change in hip extension absolute rotational work from baseline. Dashed lines indicate the smallest worthwhile change threshold (± 0.20 x baseline condition group-level standard deviation).

Mean timepoint at which the distal position of the thigh on the flexing and extending hips crossed the position of the pelvis COM in the sagittal plane within-individuals and across the group are presented in Fig 5.6. Distal position of the thigh behind the pelvis COM in indicated in light blue (back-side), while distal position of the thigh in front of the pelvis COM is indicated in light green (front-side).

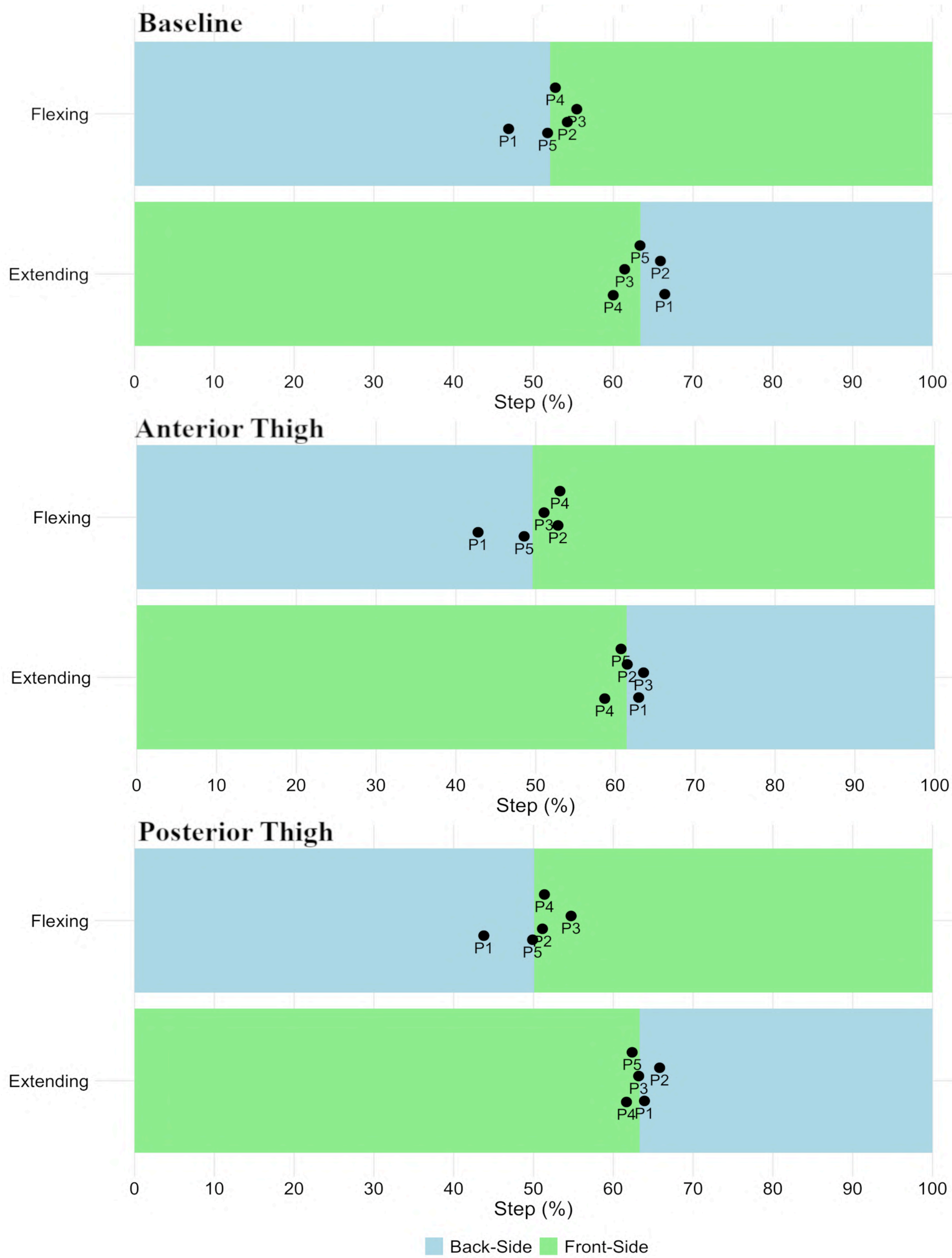

Fig 5.6 Mean proportion of distal thigh position behind (back-side) and in front of (front-side) pelvis COM on flexing and extending limbs.

5.4.4 Principal component analysis

The first two principal components explained 28.7% and 21% of the variance in the data, respectively. Top contributing variables to principal component 1 (PC1) were COM mean velocity, hip flexion power, hip flexion moment, and hip flexion absolute rotational work. Top contributing variables to principal component 2 (PC2) were ground contact time, hip extension angular velocity, braking impulse, and the "front-side mechanics" metric (inversely correlated) on the flexing limb. Distribution of sprint trials along PC1 and PC2 with K-means clustering is displayed in Fig 5.7.

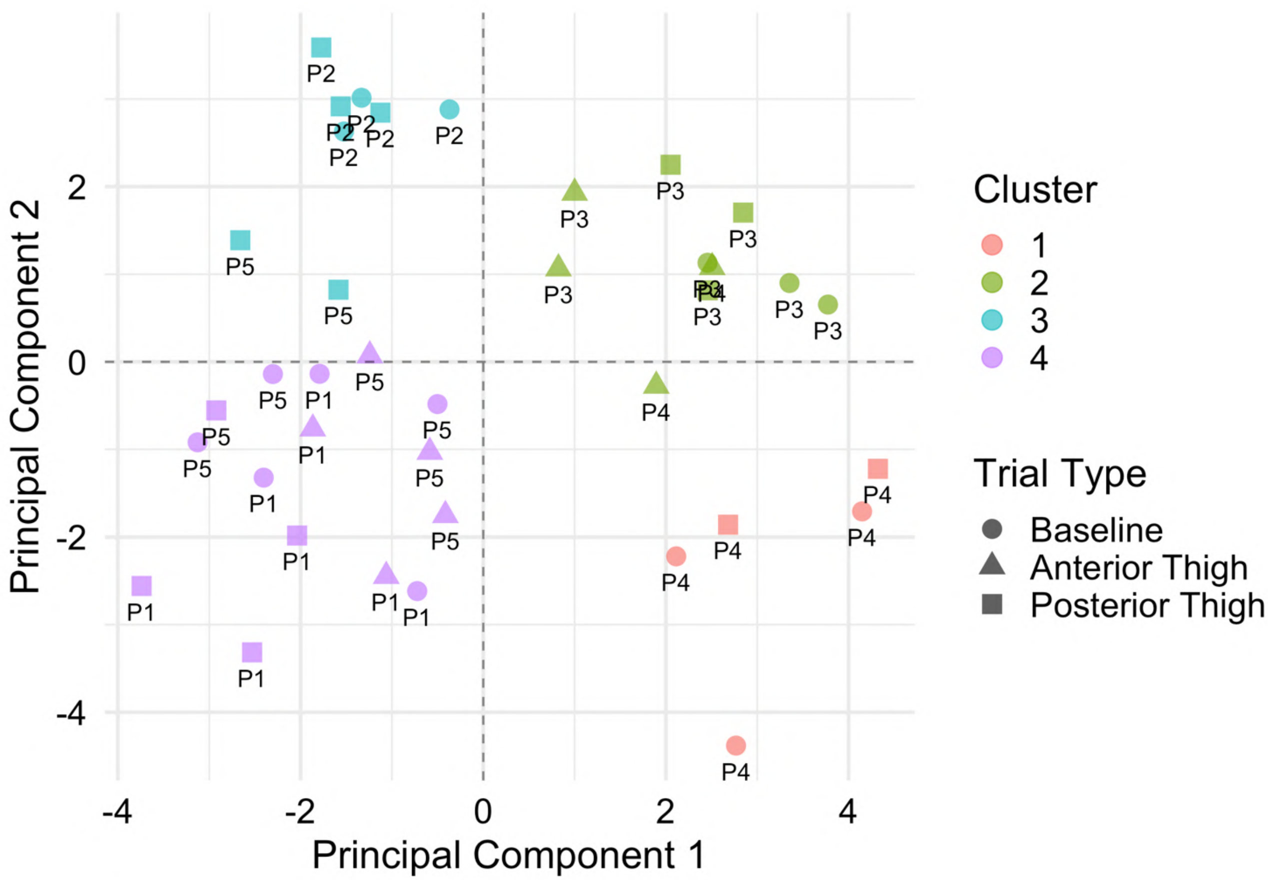

Fig 5.7 Distribution of principal component scores for kinetic and kinematic metrics and clustering of each sprint trial.

Colours indicate trial cluster designation based on K-means clustering. Shapes indicate experimental condition. Labels indicate participants.

5.5 Discussion

This study sought to investigate the effects of anterior and posterior thigh WR on whole body and hip joint-level kinetic and kinematic measures, and their interrelationships, during the late acceleration phase of sprinting among Australian Rules football players. COM mean velocity at the 16 m mark was lower in the anterior thigh WR condition than baseline in three of the five participants, and lower in the posterior thigh WR condition than baseline in four out of five participants. Anterior thigh WR increased peak propulsive force and propulsive impulse compared with baseline and the posterior thigh WR condition in most cases. Average hip flexion moment decreased with the addition of WR compared with baseline in all instances except the anterior thigh WR condition in one participant. Lastly, average rotational work during hip extension was highest in the posterior thigh WR condition in four out of five participants. These findings offer insights into the specific kinetic factors that were emphasised in each condition. There appeared to be a limited effect of WR on expression of "front-side mechanics", i.e. thigh positioning anterior to the pelvis COM on the flexing or extending limb. There was no clear clustering pattern of trials from each testing condition along the two main principal components of the data. Trials from individual participants did tend to cluster together, however, reinforcing the merit of consideration for the effects of interventions within-individuals.

In the pursuit of developing acceleration performance, training interventions may acutely diminish performance, but provide value through effects on some relevant neuromuscular or technical factor(s). For example, weighted sled resisted acceleration decreases 5 m sprint time but increases net horizontal impulse, which is likely a beneficial training stimulus if this is a performance limiting factor (Kawamori et al. 2013). In the present study, both WR conditions generally resulted in poorer sprint acceleration performance as indicated by COM velocity at 16 m. This aligns with previous findings of decreased 20 m sprint time with application of anterior and posterior thigh and shank WR (Macadam et al. 2017b), slower 50 m sprint time with application of distal thigh WR (Macadam et al. 2021a), and decreased maximum velocity in 50 m sprints with instances of both shank WR application and distal thigh WR application (Feser et al. 2021b). In all of these cases, WR is suggested as offering training benefits through "overloading" some spatiotemporal or kinetic variables, such as ground contact time (Simperingham et al. 2020), vertical impulse (Uthoff et al. 2020), braking impulse (Feser et al. 2021b), or mean rotational energy at the joint proximal to loading (Macadam et al. 2021a). Extending on these findings, the present study considered a wide array of metrics to provide greater insights into where WR effects may positively manifest for training. A novel approach to modelling the thighs and WR was also used to improve accuracy of joint-level kinetic calculations.

Most absolute whole body kinetic measures increased in WR conditions across the group, largely in agreement with previous research into lower body WR application during sprint acceleration (Simperingham and Cronin 2014; Macadam et al. 2020b; Feser et al. 2021b), though not universally (Simperingham et al. 2020). Within WR conditions, the anterior thigh WR configuration increased peak propulsive force and propulsive impulse to a greater extent than baseline and posterior thigh WR in most participants. The propensity for anterior thigh WR specifically to accentuate these kinetics during late acceleration may therefore warrant further investigation in a larger participant cohort.

For most participants, mean hip joint moment during hip flexion was lower (or less positive) in the WR conditions compared with baseline. In other words, there was slightly lower mechanical demand on hip flexion with the addition of WR. Consultation of hip flexion moment time series (Appendix Figure 3.2 A, B, and C) appeared to show that in the flexing limb, hip flexion demand was greater in the baseline condition compared with the anterior thigh WR condition at the start of hip flexion. Differences in hip flexion moment between baseline and the posterior thigh WR condition appeared to manifest at the end of hip flexion, with greater demand on hip extensors in the latter instance during this period. These findings may be worth noting for practitioners seeking to accentuate either hip flexion or hip extension demand. It must be stated, however, that the average magnitude of difference in flexing limb hip joint moment at the group level was relatively small (7.2-8.2 N·m for baseline vs. WR conditions), though the total difference would be expected to amplify across a series of steps (Bustos et al. 2020). It is also worth noting that WR effects are likely to differ throughout the course of an acceleration. In early acceleration, for example, thigh WR appears to reduce hip extension angular velocity to a greater extent than in later phases of the sprint (Feser et al. 2023), which may incidentally explain why no clear trend in the difference in this metric was observed across conditions in the present study.

The effects of WR on hip absolute rotational work present an interesting point of discussion. When investigating addition of distal thigh WR totalling 2% of participant body mass, Macadam et al. described an increase in rotational energy between 9.8-18.8% during acceleration (Macadam et al. 2021a). Rotational energy was calculated according to $E = \frac{1}{2}I\omega^2$, where E = rotational energy (J), I = segment moment of inertia (kg·m²), and ω = segment angular velocity (radians/s). In ensuing discussion, however, the authors refer to overload of rotational work at the hip. It is important to distinguish between rotational energy and rotational work. Rotational energy describes the kinetic energy stored in an object due to its rotation at a specific instance, while rotational work, calculated from the integral of joint power over time, describes the energy transfer at the joint via torque over a given time, through rotational movement. In the present study, WR and the thigh were modelled together enabling determination of distinct inertial parameters, which were subsequently used in the calculation of hip joint torque, hip joint power, and hip joint rotational work. This approach may provide greater confidence in suggestions that the alterations to segment inertia brought about by WR increase work requirements at the hip joint during acceleration. This clearly has implications for the use of WR in training to develop neuromuscular factors related to acceleration. Interestingly, in the present study higher average hip extension absolute rotational work was primarily observed in the posterior thigh WR condition.

In addition to effects on kinetics, WR can be considered a constraint on action with possible motor learning applications (Davids 2010; Trounson et al. 2020). Maximising "front-side mechanics" during sprinting, i.e. the proportion of actions of the legs occurring in front of the body, is a common recommendation given by coaches training speed, as this is said to be a hallmark of higher performing sprinters (Young 2007; Mann and Murphy 2015). This technical approach is purported to promote greater hip extension speed, greater vertical GRF, and minimise braking forces. Although there is conjecture about the efficacy of front-side mechanics on enhancing sprint performance (Haugen et al. 2018), it remains widely used in practice. Furthermore, growing recognition of the benefits of complex systems-based pedagogy has seen implementation of constraints such as small hurdles or 'wickets' during sprinting to promote adoption of these mechanics through self-organisation (Clark 2018; Wild and Goodwin 2023). This study sought to investigate whether anterior or posterior thigh WR could have similar application. There appeared to be only a slight increase in the proportion of time that thigh position on the flexing limb was in front of the midline in both WR conditions compared with baseline. This effect was seemingly reversed for the extending limb, so the benefits of WR application for promoting front-side mechanics may depend on whether coaches want to preferentially affect the flexing or extending limb. The dominance of front-side mechanics on the flexing limb displayed by participant P1 appeared to accompany short ground contact times and high step frequency relative to other participants, though this did not appear to manifest in superior sprint performance.

PCA was used in the first instance to assess shared variation among the array of variables collected. Metrics of hip flexion, specifically hip flexion power, hip flexion moment, and hip flexion absolute rotational work, shared the most variance with COM mean velocity in the first principal component, which itself explained 28.7% of the variance in the data. This points to some relationship between these metrics and acceleration performance in the participant cohort. Subsequent clustering of trials plotted along the first two principal components was used to investigate trial distribution across testing conditions. There was no clear clustering of trials based on WR condition along the first two principal components, pointing to no clear pattern of effects on metrics with the most shared variation. As may be expected, trials from within-individual participants did tend to cluster together regardless of testing condition, providing support for ongoing calls for greater consideration of individual-based analyses in sports biomechanics (Bates et al. 2004; Yeadon 2005).

In terms of study limitations, findings may have limited generalisability given the small sample size. The analytical approaches and novel WR modelling are, however, transferable to larger cohort studies, and the findings may offer starting points for coaches. In the present study, only movement the sagittal plane was analysed, since WR was positioned anteriorly and posteriorly, and this is the dominant movement arc of the hips during sprinting. However, there may have been effects of WR on other movement planes, which were not captured. Lastly, although testing sessions for each participant were separated by at least 1 week, it is possible that a learning effect may have impacted the assessed variables, independent of the effects of WR. Future research may further investigate findings from the present study in a larger participant group, and/or study the longitudinal effects of training with WR to determine whether the variables subject to acute overload identified herein are in fact enhanced following a dedicated WR training block.

5.6 Conclusions

Addition of WR led to an acute reduction in acceleration performance across the participant group, as well as a lower average hip flexion moment, however, the anterior and posterior thigh WR configurations did appear to accentuate certain kinetic and kinematic measures. Specifically, peak propulsive force and propulsive impulse tended to be higher with anterior thigh WR, while hip joint absolute rotational work during hip extension tended to be higher with posterior thigh WR. Particular WR configurations, or indeed sprinting without WR, may therefore be most appropriate depending on the biomechanical factor(s) coaches are seeking to emphasise. There was a slight tendency for adoption of more front-side mechanics on the flexing limb with the addition of either anterior or posterior thigh WR, however, the importance of front-side mechanics to sprint performance remains ambiguous, and is likely individual-specific.

Chapter 6 – Effects of lightweight wearable resistance on change of direction performance and segment coordination: a case study

6.1 Abstract

Rapid change of direction ability is required for effective attacking and evasive actions in field-based sports. Change of direction performance is influenced by several potentially trainable factors, including technical execution. Increasingly, prescriptive technical models are deemphasised in the coaching of technique. Instead, complex systems-based pedagogical approaches, such as manipulation of constraints and differential learning, are being implemented. Wearable resistance presents a novel constraint in these frameworks. A single subject underwent three testing sessions – baseline (no wearable resistance), fixed trunk wearable resistance (2.5% of bodyweight on the contralateral side of the trunk to the change of direction), and random segment wearable resistance (2.5% of bodyweight randomly varied across body segments between repetitions). Each testing session involved 10 repetitions of a 110 degree maximal effort change of direction task. Triplanar pelvis and thorax kinematics were measured and segment coordination calculated. Change of direction performance was superior in the random segment wearable resistance condition and there was a higher proportion of anti-phase segment motion and coordination variability between segments. Technique improvements from this condition may be conferred through exposure to a variety of potentially beneficial movement patterns. Fixed trunk wearable resistance had little effect on performance or segment coordination compared with baseline change of direction. Repetition-to-repetition variations in wearable resistance configuration during change of direction may warrant further investigation in a larger participant cohort to determine the group-level effects and pedagogical utility of this approach.

6.2 Introduction

The ability to change direction rapidly is essential for athletes in field based sports such as Australian Rules football, soccer, and rugby codes (Lockie et al. 2013). Not only is there a high frequency of change of direction (COD) events, with more than half of all sprints in Australian Rules football involving a COD (Dawson et al. 2004), but COD performance has also been identified as a factor distinguishing elite and sub-elite soccer players (Reilly et al. 2000b). From the outset, it is important to differentiate COD from agility, which includes the processes of perception and decision-making in a competitive context (Sheppard and Young 2006). Indeed, the value of training COD for field-based athletes has been contested, given weak relationships between COD and agility performance (Matlák et al. 2016; Sheppard et al. 2006). However, it is likely that COD ability establishes athletes' action capabilities for agility manoeuvres, with weak relationships between tests attributable to variations in the perceptual components of agility (Wilson et al. 2018; Wilson et al. 2021; Gabbett et al. 2008; Kadlec et al. 2023).

COD ability is influenced by the interactions of several factors, most notably; neuromuscular capacities (e.g. lower body power and rate of force development), athlete anthropometry, technique, approach velocity and the angle of direction change (Sheppard and Young 2006; Dos'Santos et al. 2018). Of these factors, training interventions to enhance neuromuscular capacities have received the most research and practical focus (Asadi et al. 2016; Brughelli et al. 2008). Plyometric, strength, sprint, COD, post-activation potentiation, and combination training have been investigated extensively with respect to their effects on COD performance (Nygaard Falch et al. 2019). While a number of coaching texts do suggest technical models for improvement of COD performance (Brown et al. 2014; Dawes and Roozen 2011; Cissik and Barnes 2004), associated evidence for the effectiveness of these models is not always provided. Recent work by Jones and Dos'Santos (2023) has gone some way towards addressing this gap, citing research demonstrating improvements in COD performance among soccer players (Dos'Santos et al. 2019) and multidirectional sport athletes (Dos'Santos et al. 2021a) following a period of technique modification training (Jones and Dos'Santos 2023). This work also acknowledges the complexity associated with technique modification interventions, such as individual response variation to training in line with a particular technical model (Wild and Goodwin 2023), that technical changes follow a nonlinear time course (Meyers et al. 2023), and that there is interdependence between factors contributing to COD performance (Dos'Santos and Jones 2023a).

Increasingly, there is consideration for the use of complex systems-based pedagogical approaches in strength and conditioning when attempting to intervene on the technical execution of general athletic skills such as COD, acceleration, and jumping (Nimphius 2017; Wild and Goodwin 2023; Kadlec et al. 2023; Brearley and Bishop 2019). Such approaches challenge notions of fixed technical models for actions and recognise movement as emergent and arising from the interaction of task, organismic, and environmental constraints (Newell 1986; Kelso 1995; Davids et al. 1999; Davids et al. 2008b). Consideration of athletes' intrinsic behavioural dynamics is given, and inter-repetition execution variability allowed as part of the athletes' search for diverse movement solutions (Handford 2006; Nimphius 2017; Caldeira et al. 2023). This fosters adaptability in the movement system, allowing task performance to be maintained when constraints vary (Chow et al. 2011; Orth et al. 2018; Caldeira et al. 2023).

The constraints-led approach to motor learning is a specific complex systems-based pedagogical approach, wherein implementation or manipulation of constraints is used to direct movement expression (Renshaw et al. 2010; Renshaw et al. 2019). For example, implementation of wickets (small hurdles) during sprinting requires high swing leg recovery in order for successful sprint execution without hitting the markers, while horizontal spacing of wickets can act as a control parameter for step length (Wild and Goodwin 2023). Differential learning is another pedagogical approach arising from a complex systems view of human movement (Schöllhorn et al. 2012). This approach seeks to facilitate technical development by maximising exploration of movement solutions to a task through the addition of random perturbations (Savelsbergh et al. 2010; Schöllhorn 2016). Both approaches have shown promise with regard to improving performance outcomes (Savelsbergh et al. 2010; Gaspar et al. 2019; Gray 2020) and increasing execution variability (Lee et al. 2014; Barris et al. 2014) of sporting actions. With growing support for complex systems-based pedagogical approaches in strength and conditioning, both methods warrant investigation for their effects on COD action and performance.

Lightweight wearable resistance (WR) applied to body segments is a potentially versatile training tool, which can be deployed both to increase ("overload") joint work during specific actions (Macadam et al. 2021a; Macadam et al. 2021b) and as a control parameter in complex systems-based pedagogical frameworks (Trounson et al. 2020). Concentrating on the latter, where there has been comparatively less research, there is merit in beginning to describe how WR influences the behavioural trajectories adopted during COD when applied in either a fixed (aligning with a constraints-led approach) or randomly varying (aligning with a differential learning approach) manner. This represents the overarching aim of the present study.

In the pursuit of integrating complex systems approaches with strength and conditioning practice, extensive research possibilities exist, so discretion must be used to focus aims, while recognising the limits of application of findings and the elements of complexity that are not being investigated. In this instance, the specific aim is to describe the acute effects of fixed and randomly varying WR on thorax and pelvis coordination during a 110 degree COD task in an Australian Rules football player. The adoption of a single subject design with specific attention on the movement coupling of proximal structures strongly implicated in COD performance (Marshall et al. 2014) serves as an initial, yet detailed, investigation into this area. It is expected that pelvis-thorax coupling will be meaningfully altered during COD when WR is applied in a fixed manner on the thorax, and that this will positively impact COD performance relative to baseline. It is also expected that there will be greater between-trial pelvis-thorax coordination variability when WR configuration is varied randomly between trials.

6.3 Materials and methods

6.3.1 Participant details

A single male professional Australian Rules football player (age: 22.8 years; height: 195.4 cm; body mass: 95.86 kg) was recruited for participation in this study. The individual was undertaking team football training three times per week and had no prior experience with WR. During the testing period, the participant's average weekly running volume was 30-45 km. The participant was also exposed to change of direction events of varying intensities as part of their football training over the testing period. They provided written informed consent and were free from musculoskeletal injury at the time of, and in the 6 months prior to, testing. All procedures used in this study complied with the criteria of the declaration of Helsinki and ethical approval was granted by the Victoria University Human Research Ethics Committee (HRE19-020).

6.3.2 Procedure

6.3.2.1 Study design

Testing was undertaken in the Biomechanics Laboratory at Victoria University, Footscray Park, Melbourne, Australia. The participant attended the laboratory on four occasions in total, comprising one familiarisation session, one baseline testing session, and two WR testing sessions. Each testing session was conducted at the same time (10:00 AM) to minimise the influence of circadian variation, and was undertaken at least 48 hours post-previous structured football team training. Each testing session was separated by at least 1 week. During testing sessions, the participant performed 10 repetitions of a COD effort, interspersed with 3 min rest periods. WR testing sessions involved exposure to a load equivalent to 2.5% of bodyweight (2.4 kg) in either a fixed manner on the trunk (FT), or in a randomly varying manner across several body segments (RS). In each COD effort, completion time was recorded and segment-level kinematics were captured during the cutting step.

6.3.2.2 Experimental setup

Testing was conducted on a Mondo track surface in the biomechanics laboratory. A COD task was constructed, which involved a 5 m lead-in distance, a 1.5x1.5 m area for execution of the COD plant step, and a 5 m exit distance at an angle of 110 degrees to the lead-in direction (Fig 6.1). The direction of the COD was defined such that the plant step would be performed on the participant's dominant foot (in this case the right foot). Infrared timing gates (Smart Speed, Fusion Sport, Brisbane, Australia) were situated at the start position, immediately in front of the plant step zone (i.e. 4.25 m from the start position), and at the finish position. In each effort the participant adopted a left foot forward 2-point upright starting stance, with the front foot situated 0.9 m behind the starting line. Timing began when the timing gates at the start position were triggered by the participant commencing their effort. The participant was provided with feedback on completion time following each effort. Motion analysis cameras were arranged around the plant step zone and the approximate capture volume was 4.0 m long, 2.5 m high, and 3.0 m wide. A 13-camera VICON motion analysis system (T-40 series, Vicon Nexus v2, Oxford, UK) sampling at 250 Hz was used for collection of segment-level kinematic data. In Vicon Nexus software, a global reference system was defined with the positive Y-axis horizontal in the direction of the finish line. The positive X-axis was perpendicular to the Y-axis, horizontal in the left direction (Fig 6.1). As such, this axis was offset by 20 degrees from the start line of the sprint. The positive Z-axis was in the vertical direction. A total of 42 reflective markers with 12.7 mm diameter were attached to body landmarks on the trunk, pelvis, thighs, shanks, and feet according to the Plug-In Gait model (Nexus 2023).

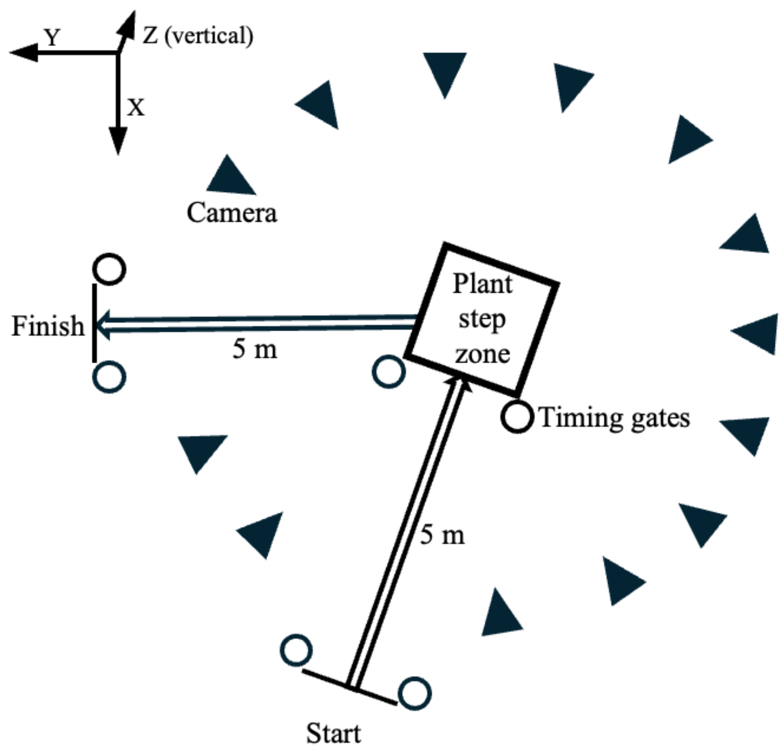

Fig 6.1 Experimental setup of COD task, location of motion analysis cameras, timing gates, plant step zone, and orientation of global reference system.

6.3.2.3 Wearable resistance

In all testing sessions, the participant wore Lila™ Exogen™ (Sportboleh Sdh Bhd, Kuala Lumpur, Malaysia) compression vest, shorts, calf sleeves, and forearm sleeves. During WR testing sessions, a combination of 100 and 200 g "teardrop" shaped loads totalling 2.4 kg were attached to the compression garments. In the FT condition, 6x200 g loads were attached to the right anterior and posterior trunk in a lateral dominant orientation (Fig 6.2). This configuration was selected to increase the inertial effects of a leftward change of direction effort, and to manipulate the participant's centre of mass away from the intended direction of movement (LaFiandra et al. 2003). In the RS condition, loading was randomly varied across 16 possible regions defined by left or right, anterior or posterior, and trunk, thighs, shanks, or forearms. Due to constraints on surface area, maximum loads in a given region were set at 1200 g for a trunk region, 600 g for a thigh region, 300 g for a shank region, and 200 g for a forearm region. A region was selected at random and maximally loaded before the next random selection was made, with load increasing additively until 2.4 kg total was achieved. 200 g loads were used on the trunk and thighs, while 100 g loads were used on the shanks and forearms. WR loads were placed in an alternating orientation on segments. RS condition loading configurations for each COD effort are presented in Table 6.1. An example of the RS condition for COD effort 1 is provided in Fig 6.2.

Table 6.1 Wearable resistance configurations and magnitudes in the randomly varying segment condition for each change of direction effort.

	Left								**Right**							
COD	**Anterior**				**Posterior**				**Anterior**				**Posterior**			
effort	**Trunk**	**Thigh**	**Shank**	**Forearm**	**Trunk**	**Thigh**	**Shank**	**Forearm**	**Trunk**	**Thigh**	**Shank**	**Forearm**	**Trunk**	**Thigh**	**Shank**	**Forearm**
1	1200 g		300 g											600 g	300 g	
2	1200 g						200 g			600 g		200 g				200 g
3			300 g		1200 g		300 g					200 g			300 g	100 g
4	1000 g								1200 g							200 g
5			300 g		900 g	600 g				600 g						
6		600 g	300 g		1200 g					300 g						
7			300 g		1200 g			200 g				200 g	200 g		300 g	
8		600 g				600 g	300 g		400 g		300 g					200 g
9					1200 g			200 g			300 g		100 g	600 g		
10				200 g		600 g							1000 g	600 g		

COD, change of direction.

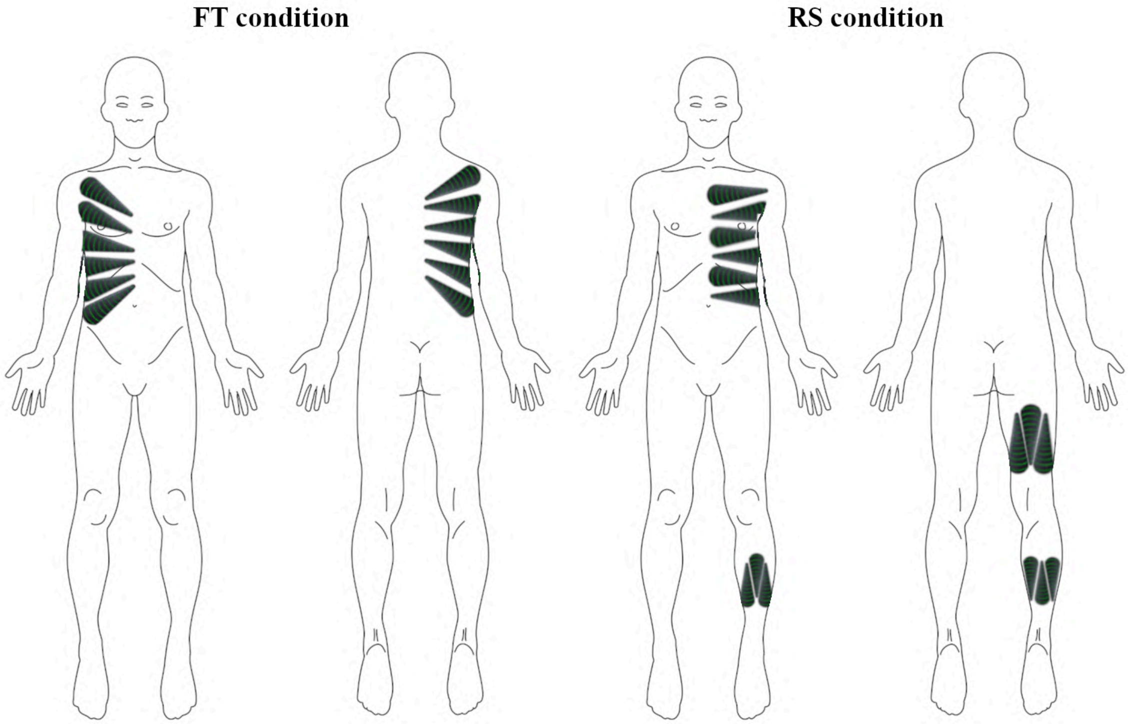

Fig 6.2 WR load configurations in FT condition and RS condition from COD effort 1. Larger size loads represent 200 g loads. Smaller size loads represent 100 g loads.

6.3.2.4 Data collection

Following application of compression garments and attachment of reflective markers, the participant undertook a warm-up consisting of a series of dynamic mobility drills, a series of forward and lateral lunges, four 5 m sub-maximal acceleration and deceleration efforts, three sub-maximal COD efforts in the testing area, and one maximal COD effort in the testing area. In the WR testing sessions, WR was applied to the requisite areas following the warm-up. The participant then performed 10 recorded maximal COD efforts interspersed with 3 mins rest. The only instructions provided to the participant were to move between the timing gates as quickly as possible and to ensure that their plant step was performed in the designated 1.5x1.5 m area. In the RS condition, WR configurations were altered during the rest period between each COD effort.

6.3.3 Data processing

Raw marker data were labelled in Vicon Nexus with rigid body filling used in instances of marker drop out (up to a maximum of 10 frames). Marker data were then transferred to Visual 3D software (C-motion, Rockville, MD, USA). Marker trajectories were smoothed via a fourth order low-pass Butterworth filter with 10 Hz cut-off frequency, based on mean results of residual analyses (Winter 2009). An eight segment model (trunk, pelvis, thighs, shanks, and feet) was constructed for each participant. An in-built model based function was used to determine model centre of mass (COM) position throughout each COD effort. Trials were trimmed with the start defined by the model COM crossing 3.5 m from the start position, and the end defined by the model COM crossing 3.5 m from the finish position. As such, body segment kinematics were determined over a 3 m distance across the COD region.

6.3.3.1 Segment coupling

Pelvis and thorax segment orientations in the X, Y, and Z-axes relative to the global coordinative system were calculated in Visual 3D. Segment orientations were normalised and time scaled to 101 data points (0-100% of the 3 m COD distance). Segment kinematics were read to R (version 2023.09.1+494) and a modified vector coding technique was used to quantify inter-segment coordination in each plane of motion, as described by Needham et al. (Needham et al. 2014). In this approach, segment coupling angles (γ_i) are calculated at each timepoint based on the vector orientation between two adjacent data points in time on an angle-angle plot relative to the right horizontal, with the proximal oscillator (pelvis) on the horizontal axis and the distal oscillator (thorax) on the vertical axis.

Coupling angles were categorised into four patterns representing the relative motion of the segments in the couple as follows: in-phase ($22.5° \leq \gamma_i < 67.5°$ and $202.5° \leq \gamma_i < 247.5°$), anti-phase ($112.5° \leq \gamma_i < 157.5°$ and $292.5° \leq \gamma_i < 337.5°$), pelvis dominancy (proximal; $0° \leq \gamma_i < 22.5°$, $157.5° \leq \gamma_i < 180°$, and $337.5° \leq \gamma_i < 360°$), and thorax dominancy (distal; $67.5° \leq \gamma_i < 112.5°$, $247.5° \leq \gamma_i < 292.5°$) (Chang et al. 2008). During in-phase motion, both segments are moving in the same direction in the specified axis, while in anti-phase motion the segments are moving in opposite directions. Pelvis dominancy indicates that the movement of the pelvis is greater than the thorax, and thorax dominancy indicates the opposite.

A measure of coordination variability was also determined based on pointwise standard deviation of coupling angles across COD efforts within each condition (Hamill et al. 2012; Estevan et al. 2016). This produced a time series, indicating areas of high repetition-to-repetition coordination variability within COD efforts. Average coordination variability across each condition was also determined as a summary statistic of inter-repetition coordination variability.

6.3.4 Statistical analysis

For the outcome variable of COD effort completion time based on timing gates, a non-parametric Friedman test was used to compare between conditions. For post-hoc analysis, a pairwise Wilcoxon test was applied with Bonferroni correction for multiple comparisons with a significance level of 0.05 set. The same statistical approach was used to compare category frequencies of coupling angles between conditions.

6.4 Results

6.4.1 COD completion time

Mean COD effort completion time was lower in the RS condition compared with the baseline condition ($p = 0.009$) (Table 6.2). No significant difference was apparent between the baseline and FT condition, or the FT and RS condition.

Table 6.2 Mean ± SD COD completion time in testing conditions with pairwise comparisons.

	COD completion time (s)
Baseline	2.51 ± 0.03
FT	2.48 ± 0.03
RS	2.44 ± 0.05 *

FT, fixed trunk wearable resistance; RS, random segment wearable resistance. * Significant difference versus baseline ($p < 0.05$).

6.4.2 Coupling angles

Triplanar pelvis-thorax coupling angles across COD efforts in each condition are presented in Fig 6.3. The radial time series plots depict the coupling angles across the 3 m COD distance capture area, with the start of the series at the centre of the plot and moving outwards. This provides a visual indication of the portions in the movement where segment coordination differs between conditions and planes.

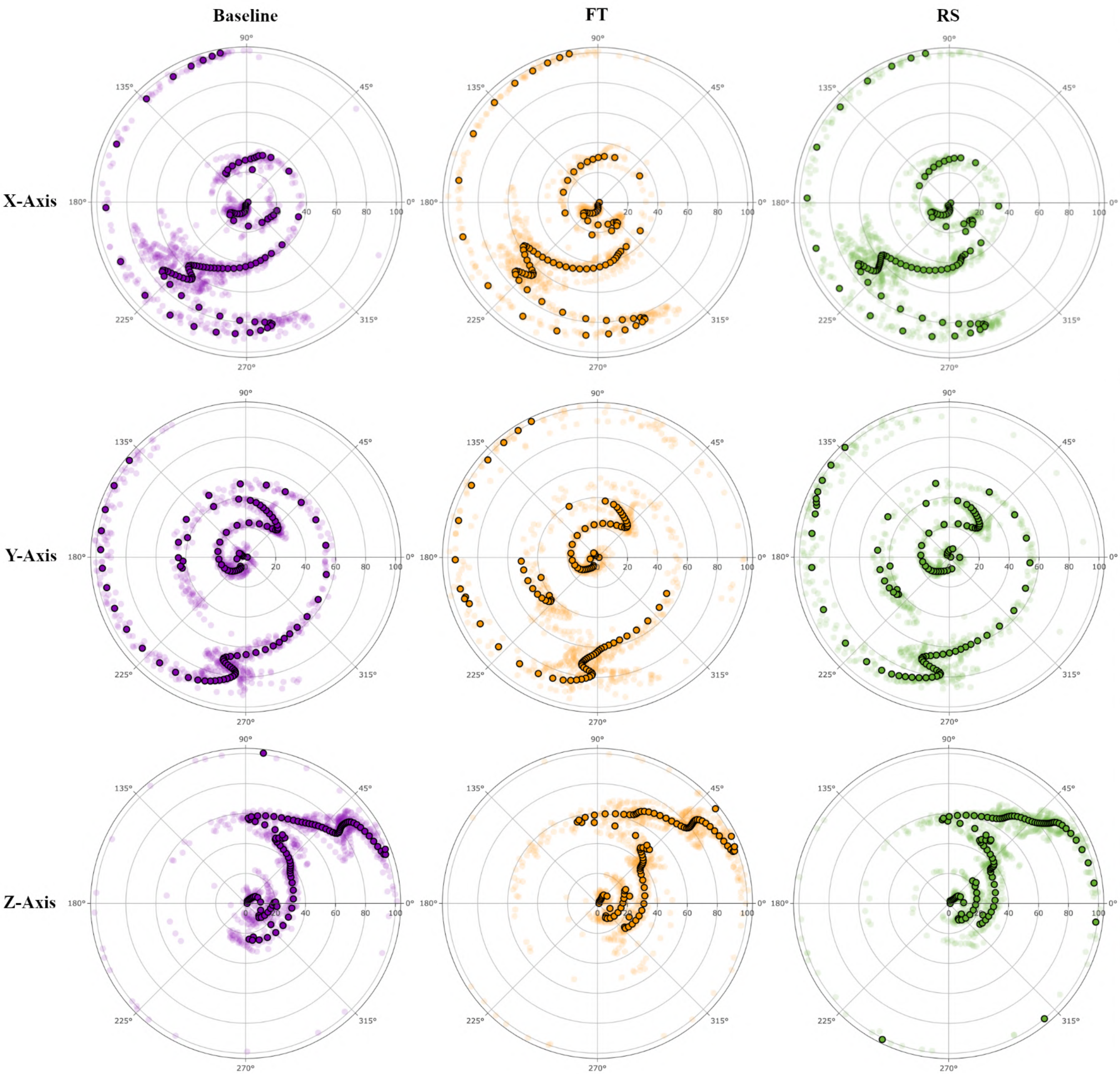

Fig 6.3 Pelvis-thorax coupling angles across COD efforts in the X-, Y-, and Z-axes for each testing condition. Opaque markers represent average coupling angles across 10 trials. Transparent markers are all coupling angles across 10 trials.

The mean ± SD frequencies of coupling angles across the four patterns of relative motion in each plane are presented in Fig 6.4. Based on a Friedman test and post-hoc pairwise Wilcoxon test, the primary differences in the proportions of pelvis-thorax relative motion between conditions were in the amount of anti-phase movement and thorax dominancy in the X-axis. The amount of anti-phase movement was greater in the RS condition compared with the FT ($p = 0.01$) and baseline condition ($p = 0.006$). The amount of thorax dominancy was less in the RS condition compared with the baseline condition ($p = 0.03$).

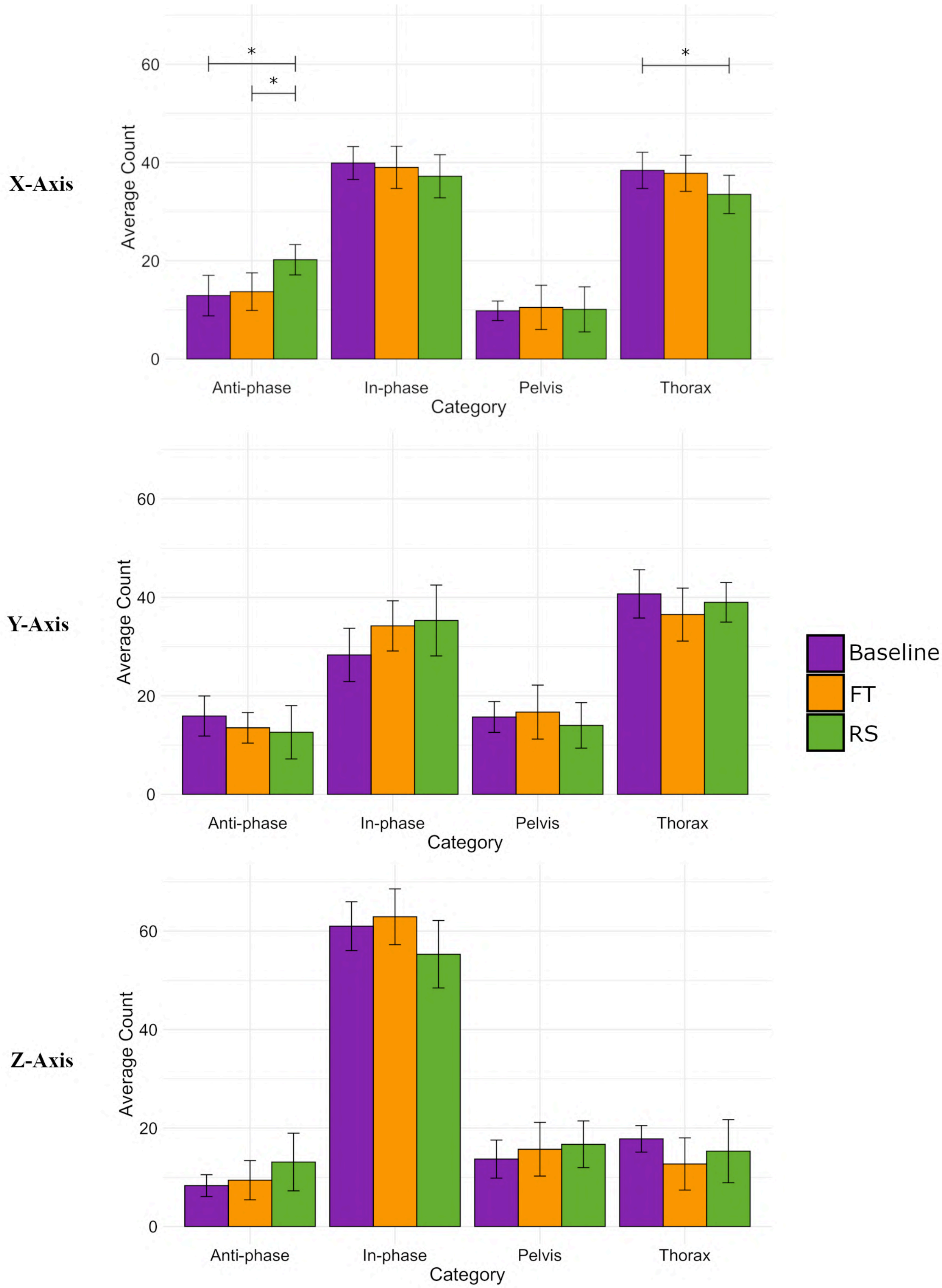

Fig 6.4 Mean ± SD coupling angle frequencies across four patterns of relative motion in the X-, Y-, and Z-axes for each testing condition. * Significant difference between

conditions ($p < 0.05$).

6.4.3 Coordination variability

Triplanar inter-repetition coordination variability across COD efforts within each condition are presented in Fig 6.5. In all planes, average coordination variability was lower in the FT condition compared with the baseline and RS conditions. In the Z-axis, coordination variability in the RS condition was greater than in the baseline and FT conditions, particularly at the midpoint and end of the capture area of the COD effort.

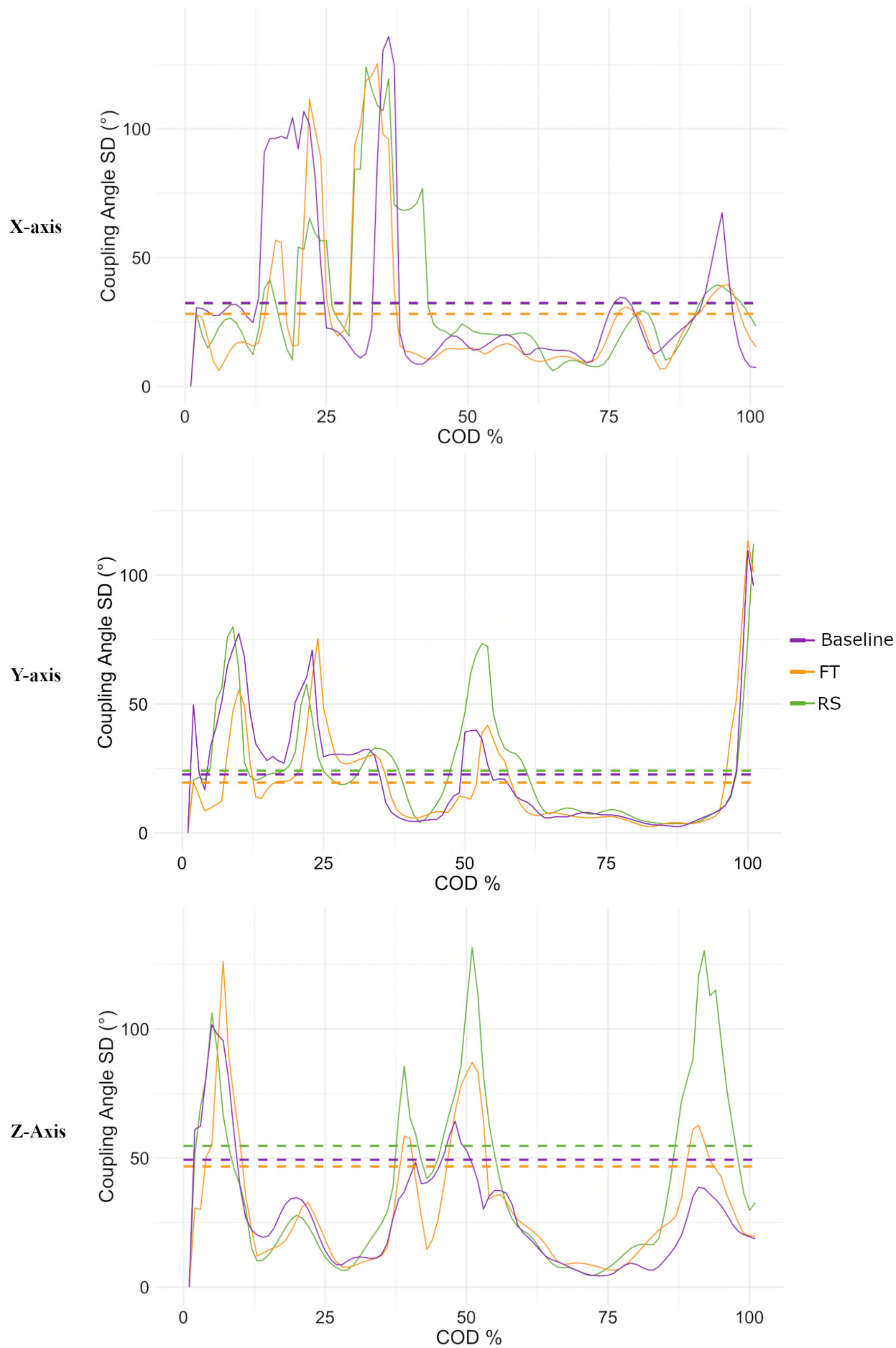

Fig 6.5 Inter-repetition coordination variability across COD efforts in the X-, Y-, and

Z-axes for each testing condition. Solid lines represent the coordination variability as a time series across the COD efforts. Dashed lines represent the average coordination variability across the COD efforts.

6.5 Discussion

This case study sought to assess the acute effects of fixed and variable WR application on COD performance and the coordination of proximal segments. Performance was evaluated through COD task completion time. Modified vector coding and coupling frequency analysis were used to assess WR effects on coordination patterns, while time series inter-repetition standard deviations of pelvis-thorax coupling angles defined coordination variability. The participant in question exhibited the fastest COD effort completion times on average in the RS condition. This was accompanied by more anti-phase pelvis-thorax coupling and less thorax dominancy of movement in the X-axis (i.e. in the plane perpendicular to the finish line). This was also accompanied by greater inter-repetition coordination variability, particularly in the Z-axis (transverse axis) compared with COD efforts in baseline and FT conditions. Given randomly varying WR in a quasi-differential learning approach appeared to acutely improve COD performance and increase execution variability, further exploration of this approach may be warranted in a larger participant cohort.

The effects of WR application in a fixed configuration on the trunk (FT condition) were investigated in line with the pedagogical potential of WR as a constraint to direct emergent movement (Trounson et al. 2020). It was expected that WR application on the contralateral side of the trunk relative to the COD would lead to technical alterations that would enhance performance, possibly mediated by the increased thoracic rotation moment of inertia (LaFiandra et al. 2003). If angular velocity could be maintained, an increase in proximal angular momentum could amplify the angular momentum in distal segments during the cutting step (Putnam 1993). In this participant, however, there was little effect of trunk WR on performance or thorax-pelvis movement coupling. These findings align with similar research demonstrating limited impact of trunk positioned WR in the form of a weighted vest on performance and COD technique among soccer players performing a 45 degree COD (Li et al. 2021). Interestingly, in the present study repetition-to-repetition coordination variability was lowest in the FT condition, suggesting reduced exploration of movement solutions to satisfy the task (Seifert et al. 2014a). Coupled with the lack of improvement in task performance, this WR application configuration therefore appears to be suboptimal from a training standpoint for this participant. It is worth considering, however, that positive effects on performance or coordination variability could manifest immediately following removal of WR or following a period of training with WR in this configuration.

Random variation in the configuration of WR (RS condition) was investigated in line with a differential learning approach to skill acquisition. COD performance was superior in this condition on average compared with baseline and FT conditions, possibly due to greater exploration and detection of novel technical strategies enabling faster completion times. Given the single subject design, however, and despite the inclusion of a familiarisation testing session, it should be acknowledged that the better performance observed in this condition could have resulted from a learning effect across the previous sessions. This order effect represents a limitation of the present methodological approach. In terms of segment coordination, the greater proportion of anti-phase coupling and reduced thorax dominancy observed in the X-axis in the RS condition was likely due to the presence of trials including lower limb WR. Although an exact mechanism is speculative, it is reasonable to suggest that the need to manage increased and variable lower limb loads may have altered pelvic motion (Meuleman et al. 2013). Interestingly, among throwers, a period of anti-phase segment coupling appears favourable to maximise the oblique stretch shortening cycle, increasing trunk rotation velocity (Young et al. 1996; Fleisig et al. 2013). A similar phenomenon may facilitate COD performance, noting findings indicating greater lateral rotation of the thorax towards the finish line during a 105 degree COD task is associated with faster completion times (Marshall et al. 2014). However, this would point to anti-phase segment coupling manifesting predominantly in the (transverse) Z-axis, which was not the case in the present study.

As expected, average between-trial pelvis-thorax coordination variability was highest in the RS condition across all planes, particularly in the Z-axis. Clear spikes in variability in the Y- and Z-axes were evident at around 50% of the COD task, corresponding with the plant step, and beyond 90% of the capture area during the second reacceleration step towards the finish line. Given the functional role of variability in training, exposure to varying WR configurations during COD was likely beneficial for the study participant and appears to warrant further investigation among a larger participant cohort and in other general athletic skills (Barris et al. 2014; Hamacher and Zech 2018).

Existing research into technique modification in COD has shown that a six week training block can result in COD performance improvements and technical changes (Dempsey et al. 2009; Dos'Santos et al. 2019; Dos'Santos et al. 2021a; Dos'Santos et al. 2022). The interventions in these studies involved verbal instructions and corrections from a coach in line with a technical model of COD derived primarily from minimisation of knee abduction moments (Dos'Santos et al. 2021b). Externally directed cues were used and knowledge of performance feedback provided. In the present study, only knowledge of results (COD completion time) were provided to the participant, requiring implicit repetition-to-repetition adjustments for performance to be improved. Interestingly, task variability was high in the training studies referred to, with approach speed, turn angle, reaction stimulus, and the presence of sport specific stimuli all being varied across the training period. Distinguishing between the performance benefits derived from variability and knowledge of results feedback alone versus with coaching interventions presents an interesting adjunct to this research with implications for training design and pedagogy.

The primary limitation of the present study is the lack of generalisability of findings due to the single subject design. The value of individual-level investigations is being increasingly acknowledged, however, given practically relevant changes may be masked in group-level analyses, and pedagogical interventions aimed at altering movement technique are often individual-based (Ball and Best 2012; Dingenen et al. 2018; Horst et al. 2020). As previously alluded to, it is possible that there may have been a learning effect of the COD task across testing sessions despite familiarisation, with the magnitude of this effect not known. This impacts the reliability of conclusions. Incorporation of a final baseline condition could have gone some way to clarifying the extent of the learning effect and should be included in similar future studies.

6.6 Conclusions

Random repetition-to-repetition variation in WR configuration resulted in superior COD performance and greater coordination variability in pelvis-thorax movement coupling compared with baseline and a fixed trunk WR configuration. The application of random perturbations to a task, in line with a differential learning approach, may be an effective pedagogical strategy by exposing an individual to a wide array of potentially useful movement techniques. Fixed trunk WR was also investigated for its utility as a COD movement control parameter, however, there was limited effect on performance or pelvis-thorax coordination, and an apparent reduction coordination variability. While constraint implementation can serve a pedagogical purpose by guiding movement towards particular favourable patterns, this was not the case with fixed trunk WR in the present study. Future research into variable WR application during COD is warranted in a larger participant cohort, or across a longer exposure period, to further characterise the effects of this type of intervention.

Chapter 7 – Discussion and conclusions

7.1 Discussion

This thesis aimed to explore the acute effects of WR on the coordination and performance of general athletic skills among field-based sport athletes. Submaximal overground running, early and late acceleration, and COD were investigated specifically. The effects of WR on coordination patterns and their levels of variability were evaluated to describe the potential utility of WR as a movement control parameter in a complex systems-based pedagogical framework. This information is worthwhile given the recent emergence of such pedagogical approaches in field-based sport strength and conditioning coaching for bringing about technical changes to general athletic skills. While effective implementation of these approaches has been demonstrated in sport skill pedagogy (Lee et al. 2014; Verhoeff et al. 2018; Santos et al. 2018; Gray 2020), less research has been conducted in strength and conditioning coaching specifically (Brearley and Bishop 2019; Kadlec et al. 2023), and no research to date has considered WR in this manner.

Though not the central the aim of the thesis, a logical discussion starting point is the effects of WR on performance outcome measures. These are likely to be of initial concern to many coaches, and this enables findings to be situated within the existing body of WR literature. In sub-maximal running, requisite running velocity was able to be maintained by participants with the addition of lower limb WR up to 3% of body weight, beyond which point velocity decreased. Based on COM velocities, group-level acute performance decrements were also evident during early acceleration in the majority of WR conditions, and late acceleration in anterior and posterior thigh WR conditions. WR did not negatively impact single subject COD performance. The trend for WR to acutely diminish performance during athletic movements is somewhat unsurprising given the overall increase in system mass contributing to greater body inertia, increased force production requirements, and energy expenditure (Martin 1985; Cronin and Hansen 2006; Macadam et al. 2020b). Similar findings of performance decrements have been demonstrated with thigh and shank WR (Feser et al. 2023), and forearm WR (Macadam et al. 2019b) during early acceleration, thigh WR at peak velocity during 10 s sprints (Macadam et al. 2021b), and thigh and shank WR during maximal velocity sprinting (Hurst et al. 2020). As with other forms of resistance (e.g. sled towing, weighted vests, or incline sprinting), coaches may tolerate performance decrements, knowing that specific kinetic or kinematic process measures will be emphasised, which is where training effects are likely to manifest.

A key area of interest was the directionality of acute kinematic and coordinative changes resulting from WR application, as an initial indication of movement states that tend to be adopted. The implication herein is that certain WR configurations and magnitudes may be useful from a pedagogical standpoint for influencing technical execution of general athletic skills. Examples from baseball hitting (Gray 2020) and weightlifting (Verhoeff et al. 2018) highlight that task constraint manipulation can shape movements. In overground running, addition of lower limb WR (anterior and posterior thighs and shanks) equivalent to 3% and 5% of body weight resulted in the maintenance of more neutral sagittal plane ankle angle during swing leg heel recovery compared with body weight only and 1% body weight WR running. Knee flexion on the stance leg during weight acceptance was greatest in the 5% body weight WR condition. These kinematic changes were likely adaptive for maintaining running speed in the presence of greater system mass, possibly through greater co-contraction of muscles around the ankle joint to maintain ankle stiffness, and increased ground reaction impulse associated with greater knee flexion (Devita and Skelly 1992; Kawamori et al. 2013). It is contestable whether these changes would confer a technical benefit worth pursuing in training. However, benefits to neuromuscular or metabolic output may be gained through interdependent kinetic changes (Macadam et al. 2017a).

In early acceleration, relatively heavy posterior thigh WR (equivalent to a 6% increase in moment of inertia about the hip in the sagittal plane across an acceleration stride) had the most marked impact on whole body coordination on average across participants. Specifically, a more neutral pelvic position and greater hip extension were observed during an early acceleration stride. Given the role of hip extension for propulsion in acceleration, heavy posterior thigh WR may have utility in encouraging adoption of this motion (Morin et al. 2015; Haugen et al. 2018). Heavy anterior thigh WR resulted in greater shoulder joint angle amplitude in the sagittal and transverse planes. This WR configuration could therefore encourage such action, though it must be acknowledged that the benefit of high arm swing amplitude for acceleration performance is disputed (Macadam et al. 2018).

In late acceleration, there was no clear trend in changes to hip flexion or hip extension angular velocity with the addition of either anterior or posterior thigh WR. There was also only a minor trend towards greater adoption of "front-side mechanics" – a technical model for sprinting advocated for by some coaches (Young 2007; Mann and Murphy 2015) – on the flexing limb in both WR conditions compared with body weight only sprinting. As with overground running, it appears that among the participant group the utility of anterior and posterior thigh WR in training may manifest primarily in relation to kinetic factors. Specifically, peak propulsive force and propulsive impulse increased with anterior thigh WR and hip extension absolute rotational work with posterior thigh WR. These findings align with previous research into lower limb positioned WR (Couture et al. 2020; Macadam et al. 2021a) and inform the expected training stimuli arising from thigh WR application during late acceleration.

In COD, WR equivalent to 2.5% of body weight was added to the individual participant's trunk in an orientation contralateral to the COD maneuver. It was expected that manipulation of the participant's COM away from the intended direction of movement would alter pelvis-thorax coordination and confer a technical benefit through amplified distal segment angular momentum during the cutting step. There was, however, little change in pelvis-thorax segment coupling. Interestingly, inter-repetition movement variability also appeared to decrease. In combination with the propensity for constraints such as WR to direct movement towards particular coordination patterns, movement variability may increase (Lee et al. 2014), decrease (Morral-Yepes et al. 2023), or become concentrated (Komar et al. 2023), likely in an individual-, skill level-, and task-dependent fashion (Oomen et al. 2022).

At this point it is necessary to discuss distinctions between acute technical alterations and retention/learning. Several investigations into different practice approaches, such as variable practice (McCracken and Stelmach 1977) and contextual interference (Shea and Morgan 1979; Hall and Magill 1995; Feghhi and Valizade 2011), demonstrate acute diminutions in task performance but superior performance in retention tests performed over subsequent weeks, i.e. learning. This raises the need to reiterate that the observations described herein should form the basis for longer term learning studies to verify that coordinative changes are consolidated into long term learning. The acute changes induced by WR as a task constraint offer insights into which loading magnitudes and configurations are worth further investigation in learning studies for specific tasks. Some acute impact on coordination, whether through increasing the likelihood of a particular pattern being adopted or destabilising a preferred pattern to induce movement variability, is a necessary precursor to motor learning over longer duration exposure.

The acute effects reported herein are also important signposts for coaches using WR in the field as an instantaneous feedback tool. The change points in coordination and relationships between kinematic changes and joint-level kinetic overload described can guide intra-session WR prescription when considered in conjunction with training goals and coach observations.

Changes in movement variability brought about by WR was a key area of interest in this thesis, given the apparent utility of variability in training (Barris et al. 2014; Hamacher and Zech 2018). Allowing for, or even encouraging, movement execution variability may promote exploration of a broad range of task execution strategies, potentially facilitating improved performance (Savelsbergh et al. 2010; Orth et al. 2017). With this said, a reduction in movement variability may be appropriate in certain instances, particularly among individuals at the coordination stage of learning exhibiting highly variable, unrefined movements with low task success (Wagner et al. 2012). In overground running, six of 14 participants exhibited increased between-run variability in mean angles at one or more joints in one or more WR conditions compared with body weight only running. Meanwhile, two participants exhibited a definitive reduction in variability, specifically at the ankle joint in the 5% body weight WR condition. Where the former instances may point to exploration and refinement of movement strategies across repetitions, the latter likely reflect constrained actions associated with a perceived large magnitude perturbation (Domingo and Ferris 2010). Within-individuals, there appears to be tipping points in movement variability levels as WR magnitudes change. These tipping points are also likely to vary based on the joint(s) (Haudum et al. 2014) and even the phase of gait in question (Koch et al. 2020). Coaches should maintain consideration for these nonlinear responses and be aware that there are likely more and less suitable matches between WR magnitudes and skill proficiency (Busquets et al. 2016).

In early acceleration, participant P2 demonstrated the least amount of variation in whole body coordination across relatively heavy and light anterior and posterior thigh and shank

WR exposures. This participant interestingly also exhibited the slowest sprint times, indicating a lower skill level. For this individual, maintaining control and stability of movement patterns in response to WR may have been prioritised to a greater extent than other participants (Hak et al. 2012). The fact that sprint performance decreased across all WR exposures within this individual supports this notion. As far as facilitating exposure to novel coordination strategies, more highly skilled participants, or at least those more comfortable with a potentially perturbing stimulus, likely derive greater benefit from WR exposure during early acceleration.

In late acceleration, the spread of data points along the second principal component, which encompassed ground contact time, hip extension angular velocity, braking impulse, and the "front-side mechanics" metric on the flexing limb was slightly greater in WR conditions for participant P5 only. This participant also exhibited only marginal reductions in performance in the presence of WR, suggesting capacity to accommodate the WR perturbation through adoption of a broader range of organisational states. Coaches are again encouraged to adopt an individual-level focus and consider whether their intention is to use WR to shape coordination, increase between- or within-repetition movement variability, or emphasise specific kinetic factors.

In COD, movement variability was assessed across repetitions in a pointwise manner throughout maneuvers, enabling variability within specific portions of the action to be assessed. For the participant in question, random variation in WR across body segments resulted in the greatest pelvis-thorax segment coordination variability on average, specifically at the midpoint of the COD maneuver in the Y- and Z-axis, and near the endpoint the Z-axis. Varying WR configuration between task repetitions, similar to a differential learning approach, shows promise as a means of increasing movement variability, and is worthy of further investigation.

Ultimately, encouraging movement variability in training enables exploration of a broad range of task execution strategies, which may facilitate technical refinement and improve adaptability (Riley and Turvey 2002; Coutinho et al. 2024). Responses to WR are nuanced, however, meaning coaches must consider athlete skill level and their ability to tolerate perturbations to the general athletic skill in question. Also important to acknowledge is that an increase in movement variability in training is not always favourable. Variability that ultimately results in an inability of the athlete to reliably achieve a performance goal or an increased risk of injury is undesirable. One may argue that the variability sought in training should also not be entirely random but instead be directed towards a range of effective coordination patterns different individuals adopt. Cluster analyses may be a useful future direction in this case to define several movement execution strategies that arise consistently across athletes for a given task. These strategies could then provide a training framework wherein athletes are exposed to each different strategy (possibly through a constraints-led approach) and can implicitly evaluate their effectiveness based on performance outcomes.

Throughout this thesis, implementation of a variety of analytical approaches across multiple data dimensions facilitated description of nonlinear relationships between WR application and movement patterns in general athletic skills. This approach is consistent with complex systems perspectives on movement. SPM t-testing enabled comparison of continuous data across the running stride cycle, rather than at discrete points, thus providing insight into specific phases of movement most influenced by WR. GAMs also model continuous data and include random effects, which accounts for variability between individuals, providing a comprehensive summary of the relationship between WR and joint kinematics with varying WR magnitudes. Bivariate functional principal component analysis captured the major directions of variation in joint coupling across the running stride. Understanding these principal variations may enable coaches to identify favourable or detrimental joint coupling patterns and implement constraints such as WR in training accordingly. Hierarchical agglomerative clustering enabled visualisation of the (dis)similarity of whole body coordination patterns during early acceleration. This information is useful in evaluating the 'global' impact of an intervention such as WR on movement. Like hierarchical agglomerative clustering, self-organising maps reduce multi-dimensional data, however, they also retain a temporal component with data mapped in two-dimensional space. This provides information regarding the phases of movement (e.g. toe-off, touchdown, etc., in acceleration) at which coordination differs due to an intervention like WR. Lastly, modified vector coding, frequency plots, and coupling variability analysis offer a comprehensive description of the interactions between two neighbouring segments and how these change as a result of an intervention. Due to relatively small sample sizes, care should be taken in generalising findings. Given the novelty of the research questions and the emphasis on complex systems themes across movement and pedagogy, the analyses presented are the most suitable approach and provide an early translational step towards practical prescriptions and signpost directions for future research.

Besides larger cohort investigations into specific loading configurations and associated movement changes, future research should explore acute changes immediately following WR removal. Unique movement after-effects may occur following WR removal, which may also have pedagogical utility (Nakamoto et al. 2012). Studies into longitudinal exposure to WR and the impact on technical expression of general athletic skills is also a logical next step. Lastly, incorporating WR in more representative contexts would further consolidate themes of complex systems in strength and conditioning coaching.

A key practical takeaway for coaches from this thesis is that WR can be used to direct individuals towards particular movement patterns (e.g. hip extension during early acceleration), induce variability (e.g. through random variation in WR placement during COD), and/or target particular kinetic factors (e.g. peak propulsive force during late acceleration), however, individual-level prescription is necessary. The value of aligning complex systems frameworks across movement, pedagogy, and analysis is also emphasized and examples given for how this may be achieved.

7.2 Conclusions

Acute implementation of WR in general athletic skills among field-based athletes predominantly led to decrements in performance consistent with increased system and body segment inertia. Importantly, WR did show some promise as a movement control parameter, encouraging hip extension when in an anterior thigh configuration during early acceleration, for example. This information has practical implications for coaches wishing to increase an athlete's hip extension during acceleration. Interdependent effects on kinetics, such as increased hip extension absolute rotational work with posterior thigh WR during late acceleration, were also observed. This finding informs the training of specific neuromuscular output using WR.

WR induced movement variability – a key component in motor learning – in several contexts, however, responses were individual-specific and nonlinear within-individuals. Skill level and WR magnitude and configuration appear to be mediating factors in the variability response to WR. This underscores the need for consideration of within-individual responses to WR and individualised prescriptions in practice. Effects of WR on coordination in general athletic skills were evaluated using analytical techniques such as SPM t-tests, hierarchical agglomerative clustering, and modified vector coding to align with the complex systems framework advocated for throughout the thesis and to adequately describe continuous and nonlinear movement changes in response to WR. Findings from this thesis may signpost future larger cohort investigations. Future research should also consider technical changes arising from long-term WR exposure and assessment of WR effects in increasingly ecologically representative settings, as technology permits.

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Appendices

Appendix 1 – Chapter 3

Appendix Table 1.1 List of legs analysed and joint angles unable to be reconstructed for analysis.

Participant: F1		Joint		
Leg analysed: Left		Hip	Knee	Ankle
Loading	Run			
BW	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
1%	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
3%	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
5%	1			
	2			
	3			
	4			
	5			
	6			

	7			
	8			
	9			
	10			
Participant: M1		Joint		
Leg analysed: Left		Hip	Knee	Ankle
Loading	Run			
BW	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
1%	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
3%	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
5%	1			
	2			
	3			
	4			
	5			
	6			

	7			
	8			
	9			
	10			
Participant: M2		Joint		
Leg analysed: Right		Hip	Knee	Ankle
Loading	Run			
BW	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
1%	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
3%	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
5%	1			
	2			
	3			
	4			
	5			
	6			

	7			
	8			
	9			
	10			

Participant: M3		Joint		
Leg analysed: Right		Hip	Knee	Ankle
Loading	Run			
BW	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
1%	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
3%	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
5%	1			
	2			
	3			
	4			
	5			
	6			

	7			
	8			
	9			
	10			

Participant: M4		Joint		
Leg analysed: Left		Hip	Knee	Ankle
Loading	Run			
BW	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
1%	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
3%	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
5%	1			
	2			
	3			
	4			
	5			
	6			

	7			
	8			
	9			
	10			

Participant: M5		Joint		
Leg analysed: Right		Hip	Knee	Ankle
Loading	Run			
BW	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
1%	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
3%	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
5%	1			
	2			
	3			
	4			
	5			
	6			

	7			
	8			
	9			
	10			
Participant: F2		Joint		
Leg analysed: Right		Hip	Knee	Ankle
Loading	Run			
BW	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
1%	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
3%	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
5%	1			
	2			
	3			
	4			
	5			
	6			

	7			
	8			
	9			
	10			

Participant: M6		Joint		
Leg analysed: Left		Hip	Knee	Ankle
Loading	Run			
BW	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
1%	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
3%	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
5%	1			
	2			
	3			
	4			
	5			
	6			

	7			
	8			
	9			
	10			

Participant: M7		Joint		
Leg analysed: Right		Hip	Knee	Ankle
Loading	Run			
BW	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
1%	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
3%	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
5%	1			
	2			
	3			
	4			
	5			
	6			

	7			
	8			
	9			
	10			

Participant: M8		Joint		
Leg analysed: Right		Hip	Knee	Ankle
Loading	Run			
BW	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
1%	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
3%	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
5%	1			
	2			
	3			
	4			
	5			
	6			

	7			
	8			
	9			
	10			

Participant: M9		Joint		
Leg analysed: Left		Hip	Knee	Ankle
Loading	Run			
BW	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
1%	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
3%	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
5%	1			
	2			
	3			
	4			
	5			
	6			

	7			
	8			
	9			
	10			

Participant: F3		Joint		
Leg analysed: Right		Hip	Knee	Ankle
Loading	Run			
BW	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
1%	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
3%	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
5%	1			
	2			
	3			
	4			
	5			
	6			

	7			
	8			
	9			
	10			

Participant: M10		Joint		
Leg analysed: Left		Hip	Knee	Ankle
Loading	Run			
BW	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
1%	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
3%	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
5%	1			
	2			
	3			
	4			
	5			
	6			

	7			
	8			
	9			
	10			

Participant: M11		Joint		
Leg analysed: Right		Hip	Knee	Ankle
Loading	Run			
BW	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
1%	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
3%	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
5%	1			
	2			
	3			
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	7			
	8			
	9			
	10			

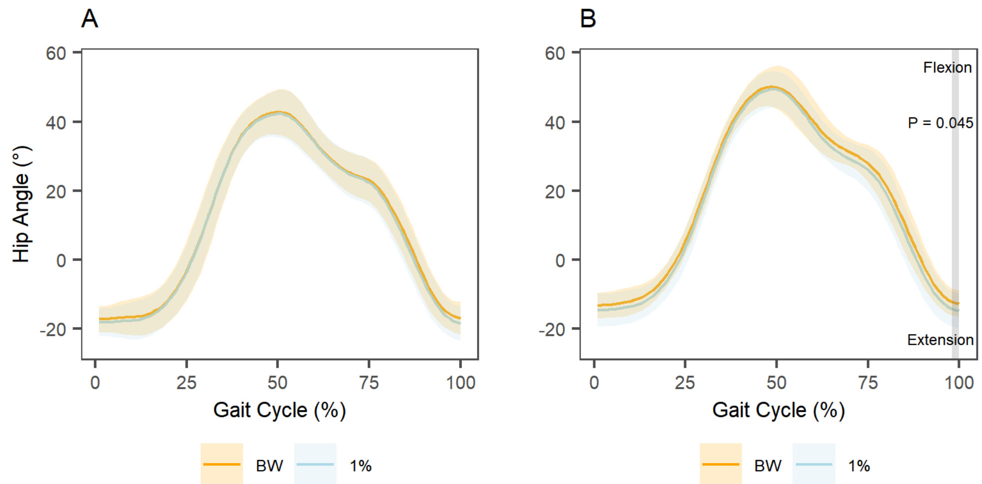
Joint angle data successfully reconstructed is highlighted in green. Joint angle data that could not be reconstructed is highlighted in red.

Appendix Table 1.2 Pointwise t-statistics and maximum critical values for SPM t-tests.

	Pointwise t-statistic								
	Hip			**Knee**			**Ankle**		
	BW vs. 1%	**BW vs. 3%**	**BW vs. 5%**	**BW vs. 1%**	**BW vs. 3%**	**BW vs. 5%**	**BW vs. 1%**	**BW vs. 3%**	**BW vs. 5%**
95% quantile	**2.65**	**2.83**	**2.84**	**2.85**	**2.87**	**2.83**	**2.64**	**2.83**	**3.04**
Gait %									
1	2.15	0.13	0.17	0.67	0.77	1.74	0.67	1.82	1.90
2	2.19	0.16	0.21	0.81	0.52	1.74	0.81	1.77	2.09
3	2.22	0.20	0.07	0.98	0.29	1.72	0.98	1.72	2.22
4	2.24	0.26	0.36	1.20	0.10	1.67	1.20	1.71	2.30
5	2.23	0.35	0.67	1.46	0.05	1.61	1.46	1.75	2.38
6	2.21	0.46	0.67	1.72	0.17	1.55	1.72	1.86	2.49
7	2.18	0.55	0.66	1.96	0.27	1.51	1.96	2.02	2.66
8	2.13	0.61	0.70	2.16	0.34	1.47	2.16	2.22	2.87
9	2.07	0.66	0.75	2.31	0.40	1.44	2.31	2.43	3.12
10	2.02	0.70	0.78	2.39	0.44	1.42	2.39	2.63	3.37
11	1.98	0.74	0.72	2.41	0.48	1.39	2.41	2.80	3.59
12	1.94	0.76	0.54	2.37	0.51	1.37	2.37	2.94	3.77
13	1.90	0.77	0.38	2.28	0.53	1.34	2.28	3.02	3.90
14	1.86	0.76	0.25	2.15	0.54	1.32	2.15	3.06	3.97
15	1.80	0.74	0.18	2.01	0.55	1.29	2.01	3.04	3.99
16	1.73	0.74	0.16	1.88	0.54	1.27	1.88	2.99	3.98
17	1.65	0.76	0.12	1.75	0.54	1.23	1.75	2.91	3.93
18	1.56	0.68	0.10	1.65	0.52	1.19	1.65	2.83	3.87
19	1.46	0.45	0.20	1.57	0.51	1.13	1.57	2.76	3.79
20	1.36	0.28	0.28	1.51	0.49	1.05	1.51	2.70	3.70
21	1.26	0.27	0.07	1.48	0.47	0.95	1.48	2.66	3.60
22	1.17	0.38	0.30	1.47	0.45	0.83	1.47	2.64	3.50
23	1.06	0.48	0.64	1.49	0.43	0.68	1.49	2.62	3.40
24	0.96	0.27	0.84	1.53	0.40	0.53	1.53	2.62	3.32

25	0.87	0.08	0.85	1.58	0.36	0.36	1.58	2.62	3.25
26	0.76	0.20	0.65	1.64	0.29	0.18	1.64	2.62	3.21
27	0.62	0.11	0.51	1.70	0.21	0.00	1.70	2.62	3.17
28	0.59	0.04	0.53	1.75	0.12	0.18	1.75	2.61	3.14
29	0.68	0.15	0.47	1.78	0.03	0.36	1.78	2.59	3.10
30	0.65	0.12	0.45	1.78	0.05	0.55	1.78	2.56	3.04
31	0.49	0.01	0.53	1.75	0.12	0.74	1.75	2.51	2.97
32	0.60	0.11	0.35	1.70	0.17	0.92	1.70	2.44	2.88
33	0.90	0.42	0.10	1.62	0.21	1.09	1.62	2.37	2.78
34	0.98	0.52	0.32	1.52	0.25	1.24	1.52	2.30	2.67
35	0.87	0.36	0.27	1.41	0.28	1.37	1.41	2.24	2.55
36	0.72	0.17	0.20	1.28	0.31	1.49	1.28	2.18	2.44
37	0.76	0.15	0.32	1.15	0.35	1.57	1.15	2.13	2.32
38	0.85	0.18	0.50	1.02	0.38	1.64	1.02	2.07	2.21
39	0.93	0.20	0.64	0.88	0.41	1.70	0.88	2.02	2.09
40	1.01	0.20	0.75	0.76	0.44	1.73	0.76	1.95	1.97
41	1.05	0.16	0.82	0.66	0.47	1.76	0.66	1.87	1.84
42	1.06	0.11	0.86	0.58	0.50	1.79	0.58	1.79	1.71
43	1.04	0.04	0.88	0.52	0.53	1.80	0.52	1.69	1.59
44	1.02	0.02	0.91	0.50	0.56	1.81	0.50	1.59	1.49
45	0.99	0.10	0.94	0.51	0.58	1.82	0.51	1.49	1.41
46	0.95	0.19	0.96	0.54	0.60	1.83	0.54	1.39	1.35
47	0.92	0.27	0.98	0.59	0.62	1.83	0.59	1.30	1.31
48	0.89	0.34	0.99	0.64	0.63	1.83	0.64	1.21	1.29
49	0.87	0.40	1.00	0.69	0.64	1.82	0.69	1.12	1.28
50	0.87	0.44	1.00	0.72	0.65	1.80	0.72	1.04	1.28
51	0.88	0.48	1.02	0.74	0.67	1.76	0.74	0.96	1.27
52	0.88	0.53	1.03	0.73	0.70	1.72	0.73	0.87	1.24
53	0.89	0.57	1.04	0.69	0.74	1.66	0.69	0.78	1.17
54	0.92	0.59	1.02	0.64	0.80	1.58	0.64	0.67	1.07
55	0.95	0.61	0.98	0.58	0.87	1.47	0.58	0.56	0.95
56	0.99	0.62	0.91	0.52	0.97	1.33	0.52	0.45	0.83
57	1.04	0.63	0.82	0.46	1.10	1.15	0.46	0.36	0.72
58	1.10	0.62	0.74	0.41	1.25	0.91	0.41	0.29	0.62
59	1.17	0.61	0.65	0.37	1.45	0.60	0.37	0.25	0.55
60	1.25	0.59	0.55	0.36	1.67	0.17	0.36	0.23	0.50
61	1.32	0.56	0.45	0.36	1.90	0.38	0.36	0.24	0.46
62	1.40	0.52	0.37	0.38	2.08	1.03	0.38	0.26	0.43
63	1.47	0.48	0.30	0.40	2.19	1.72	0.40	0.29	0.40
64	1.53	0.44	0.24	0.41	2.20	2.34	0.41	0.32	0.39

65	1.59	0.40	0.19	0.39	2.14	2.81	0.39	0.34	0.38
66	1.63	0.37	0.14	0.34	2.05	3.11	0.34	0.36	0.39
67	1.66	0.36	0.10	0.26	1.97	3.28	0.26	0.38	0.42
68	1.67	0.38	0.06	0.17	1.92	3.36	0.17	0.41	0.47
69	1.66	0.42	0.02	0.08	1.90	3.39	0.08	0.45	0.56
70	1.63	0.47	0.01	0.03	1.92	3.40	0.03	0.50	0.68
71	1.61	0.48	0.01	0.01	1.96	3.40	0.01	0.54	0.85
72	1.61	0.47	0.05	0.05	2.01	3.40	0.05	0.54	1.04
73	1.62	0.42	0.19	0.12	2.07	3.41	0.12	0.48	1.21
74	1.64	0.31	0.31	0.22	2.15	3.44	0.22	0.38	1.32
75	1.67	0.22	0.21	0.32	2.27	3.50	0.32	0.25	1.38
76	1.69	0.33	0.04	0.40	2.44	3.60	0.40	0.11	1.40
77	1.71	0.50	0.00	0.44	2.65	3.75	0.44	0.05	1.39
78	1.75	0.51	0.09	0.42	2.79	3.91	0.42	0.22	1.38
79	1.81	0.41	0.36	0.32	2.76	3.92	0.32	0.42	1.36
80	1.89	0.24	0.84	0.15	2.51	3.62	0.15	0.66	1.33
81	1.99	0.07	1.15	0.10	2.15	3.05	0.10	0.95	1.28
82	2.10	0.44	1.21	0.40	1.78	2.38	0.40	1.28	1.20
83	2.20	0.69	1.28	0.75	1.46	1.75	0.75	1.66	1.09
84	2.34	0.83	1.51	1.11	1.20	1.20	1.11	2.04	0.96
85	2.37	0.95	1.56	1.46	1.02	0.75	1.46	2.38	0.80
86	2.37	1.03	1.38	1.72	0.92	0.42	1.72	2.60	0.65
87	2.46	1.11	1.35	1.85	0.88	0.20	1.85	2.63	0.51
88	2.48	1.16	1.58	1.87	0.88	0.09	1.87	2.44	0.41
89	2.46	1.15	1.82	1.81	0.92	0.06	1.81	2.09	0.37
90	2.49	1.16	1.88	1.70	0.98	0.12	1.70	1.63	0.38
91	2.49	1.10	1.65	1.55	1.05	0.24	1.55	1.14	0.45
92	2.43	0.93	1.28	1.36	1.11	0.42	1.36	0.64	0.56
93	2.40	0.82	1.16	1.12	1.15	0.64	1.12	0.15	0.71
94	2.48	0.83	1.26	0.84	1.14	0.88	0.84	0.32	0.92
95	2.55	0.84	1.27	0.53	1.09	1.11	0.53	0.76	1.16
96	2.61	0.86	1.16	0.18	0.98	1.30	0.18	1.14	1.43
97	2.68	0.90	1.08	0.17	0.85	1.41	0.17	1.45	1.70
98	2.75	0.99	1.09	0.52	0.69	1.45	0.52	1.69	1.95
99	2.85	1.01	1.03	0.84	0.55	1.41	0.84	1.85	2.15
100	2.38	0.64	0.51	1.11	0.43	1.33	1.11	1.96	2.29

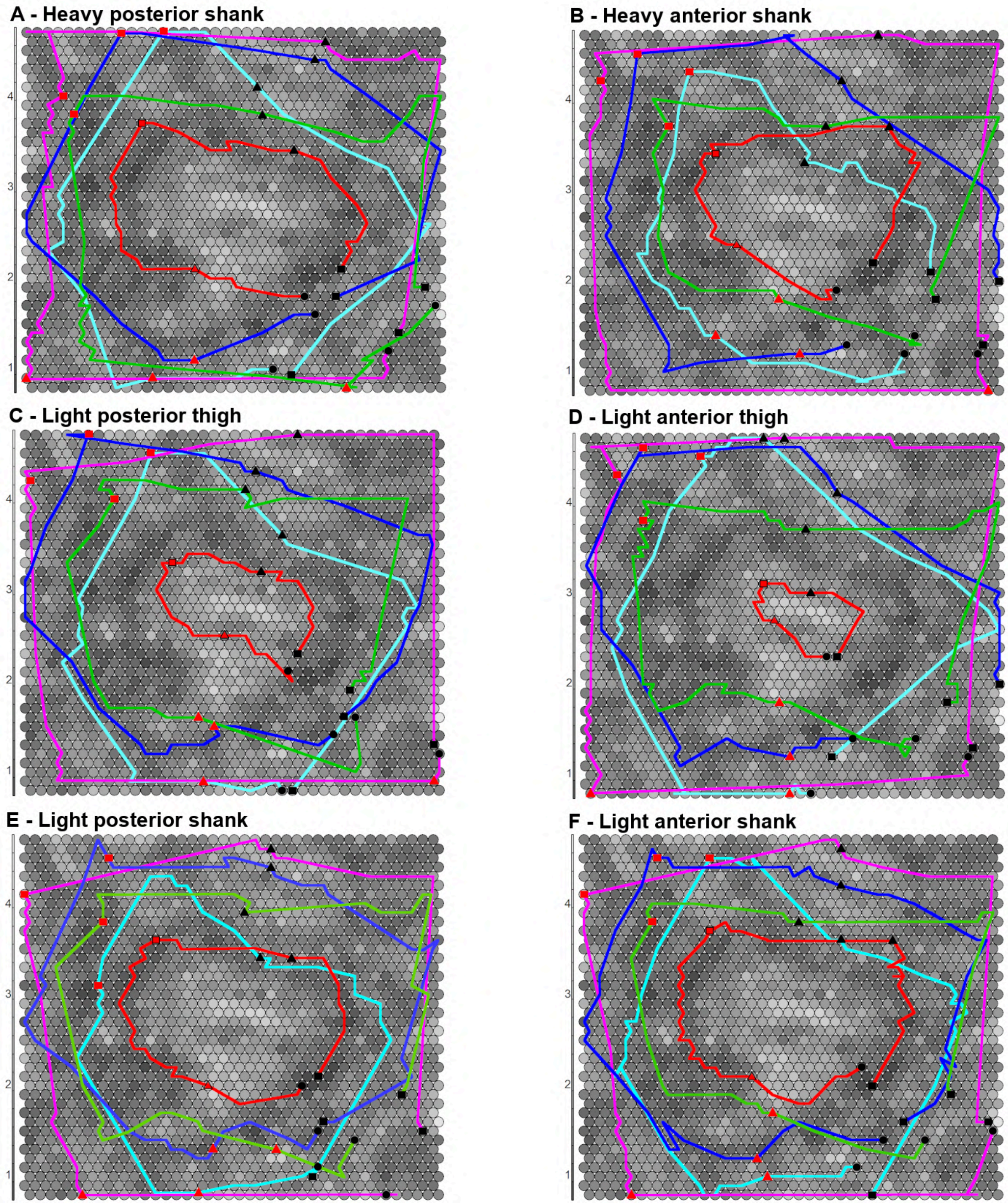


Appendix Figure 1.1 Hip joint SPM t-test BW versus 1% separated based on condition order. (A) Hip joint BW versus 1% for participants in which 1% condition did not immediately proceed 5% condition. (B) Hip joint BW versus 1% for participants in which 1% condition immediately proceeded 5% condition. Solid lines represent ensemble means and accompanying shaded regions represent ± 1 SD. Grey shaded regions indicate regions of significant difference between curve sets.

Appendix 2 – Chapter 4

Appendix Table 2.1 10 m split times and COM velocity at 4 m mark (mean ± SD).

		Baseline	HAT	LAT	HPT	LPT	HAS	LAS	HPS	LPS
10 m split (s)	**P1**	1.94 ± 0.03	1.97 ± 0.01	2.00 ± 0.05	1.97 ± 0.05	1.95 ± 0.05	1.97 ± 0.03	1.94 ± 0.02	1.97 ± 0.02	1.96 ± 0.01
	P2	2.12 ± 0.04	2.19 ± 0.08	2.25 ± 0.02	2.19 ± 0.05	2.15 ± 0.02	2.15 ± 0.04	2.16 ± 0.02	2.14 ± 0.02	2.20 ± 0.01
	P3	1.96 ± 0.05	1.99 ± 0.05	1.95 ± 0.02	1.91 ± 0.02	1.97 ± 0.02	1.97 ± 0.02	1.99 ± 0.05	2.01 ± 0.03	2.03 ± 0.05
	P4	1.89 ± 0.04	1.96 ± 0.03	1.91 ± 0.01	1.90 ± 0.01	1.91 ± 0.01	1.91 ± 0.03	1.92 ± 0.03	1.92 ± 0.01	1.90 ± 0.01
	P5	1.96 ± 0.03	1.97 ± 0.01	1.95 ± 0.01	2.01 ± 0.01	1.93 ± 0.01	1.90 ± 0.02	1.95 ± 0.02	1.94 ± 0.02	1.93 ± 0.05
	Group	1.98 ± 0.09	2.02 ± 0.10	2.01 ± 0.13	2.00 ± 0.11	1.98 ± 0.09	1.98 ± 0.10	1.99 ± 0.09	2.00 ± 0.08	2.00 ± 0.11
COM velocity at 4 m ($m.s^{-1}$)	**P1**	5.65 ± 0.11	5.54 ± 0.02	5.61 ± 0.08	5.48 ± 0.11	5.72 ± 0.04	5.61 ± 0.09	5.70 ± 0.08	5.61 ± 0.10	5.57 ± 0.03
	P2	5.42 ± 0.07	5.36 ± 0.05	5.30 ± 0.08	5.28 ± 0.08	5.43 ± 0.06	5.38 ± 0.01	5.40 ± 0.01	5.25 ± 0.04	5.39 ± 0.04
	P3	5.80 ± 0.08	5.60 ± 0.09	5.83 ± 0.04	5.79 ± 0.10	5.78 ± 0.05	5.78 ± 0.08	5.72 ± 0.08	5.62 ± 0.09	5.61 ± 0.05
	P4	5.62 ± 0.07	5.39 ± 0.14	5.53 ± 0.02	5.55 ± 0.05	5.52 ± 0.09	5.56 ± 0.08	5.51 ± 0.10	5.52 ± 0.05	5.60 ± 0.06
	P5	5.43 ± 0.25	5.70 ± 0.02	5.23 ± 0.15	5.49 ± 0.02	5.81 ± 0.11	5.44 ± 0.07	5.25 ± 0.07	5.53 ± 0.17	5.92 ± 0.04
	Group	5.59 ± 0.19	5.52 ± 0.15	5.50 ± 0.23	5.52 ± 0.18	5.65 ± 0.17	5.55 ± 0.16	5.52 ± 0.20	5.50 ± 0.16	5.60 ± 0.17



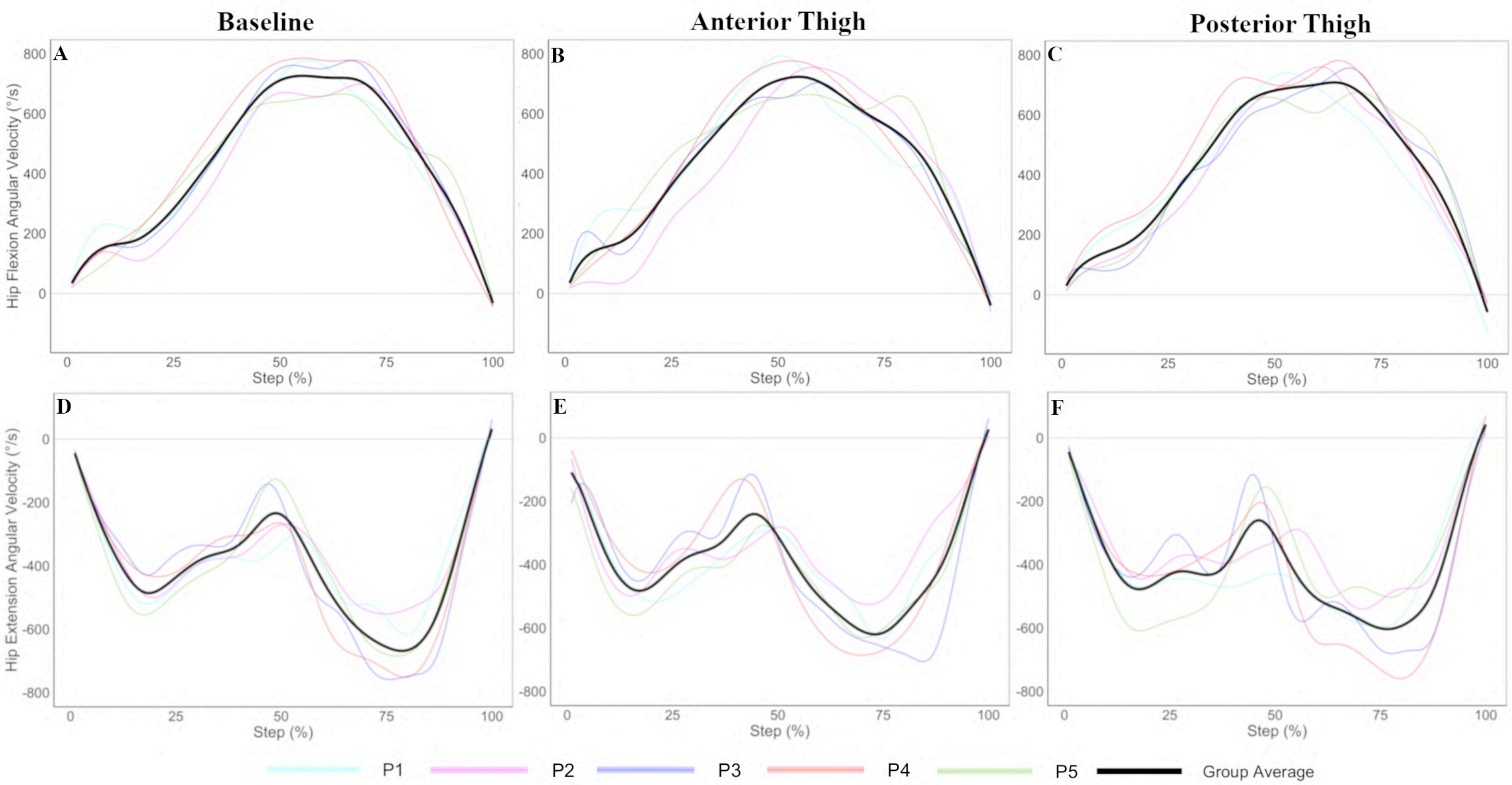
Appendix Figure 2.1 Trained SOM and best-matching unit trajectories for each participant. (A) Heavy posterior shank condition. (B) Heavy anterior shank condition. (C) Light posterior thigh condition. (D) Light anterior thigh condition. (E) Light posterior shank condition. (F) Light anterior shank condition. Participants are indicated by unique colours (light blue, P1; magenta, P2; dark blue, P3; red, P4; green, P5). Shapes and colours are used to indicate key phases of the stride cycle. Black circle, first left foot toe-off (beginning of stride) (TO_1); red triangle, right foot touchdown (TD); red square, right foot toe-off (TO); black triangle, left foot touchdown (TD); black square, second left foot toe-off (end of stride) (TO_2).

Appendix Table 2.2 Euclidian distance dissimilarity measures of joint angles between baseline and the heavy posterior thigh and heavy anterior thigh conditions.

	Baseline vs HPT			**Baseline vs HAT**		
Distance rank	**Joint/segment**	**Plane of motion**	**Distance**	**Joint/segment**	**Plane of motion**	**Distance**
1	Pelvis	Sagittal	8.52	Stance shoulder	Transverse	6.2
2	Stance shoulder	Transverse	7.1	Swing shoulder	Transverse	5.35
3	Stance hip	Sagittal	7.08	Thorax	Sagittal	5.15
4	Swing hip	Sagittal	6.88	Stance shoulder	Sagittal	5.14
5	Stance shoulder	Sagittal	5.1	Swing shoulder	Sagittal	5.09
6	Thorax	Sagittal	4.49	Stance hip	Transverse	4.73
7	Swing shoulder	Transverse	4.2	Swing hip	Transverse	4.45
8	Swing hip	Transverse	4.02	Stance hip	Sagittal	4.21
9	Swing shoulder	Sagittal	3.8	Swing hip	Sagittal	4.11
10	Stance shoulder	Frontal	3.71	Pelvis	Sagittal	3.72
11	Stance hip	Transverse	3.63	Swing knee	Frontal	3.58
12	Swing ankle	Frontal	3.28	Stance knee	Frontal	3.54
13	Thorax	Transverse	3.15	Swing knee	Sagittal	3.44
14	Swing ankle	Sagittal	2.79	Stance shoulder	Frontal	3.35
15	Stance ankle	Frontal	2.72	Swing ankle	Frontal	3.32
16	Stance hip	Frontal	2.63	Stance knee	Sagittal	3.14
17	Stance knee	Sagittal	2.57	Stance hip	Frontal	3.11
18	Stance ankle	Sagittal	2.55	Thorax	Transverse	2.92
19	Pelvis	Transverse	2.44	Swing knee	Transverse	2.82
20	Swing knee	Sagittal	2.41	Swing hip	Frontal	2.77
21	Swing knee	Frontal	2.41	Swing ankle	Sagittal	2.65
22	Swing shoulder	Frontal	2.19	Stance ankle	Sagittal	2.39
23	Stance ankle	Transverse	2.14	Swing shoulder	Frontal	2.38
24	Stance knee	Frontal	2.12	Swing ankle	Transverse	2.37
25	Swing hip	Frontal	2.11	Pelvis	Frontal	2.35
26	Swing ankle	Transverse	1.94	Pelvis	Transverse	2.34

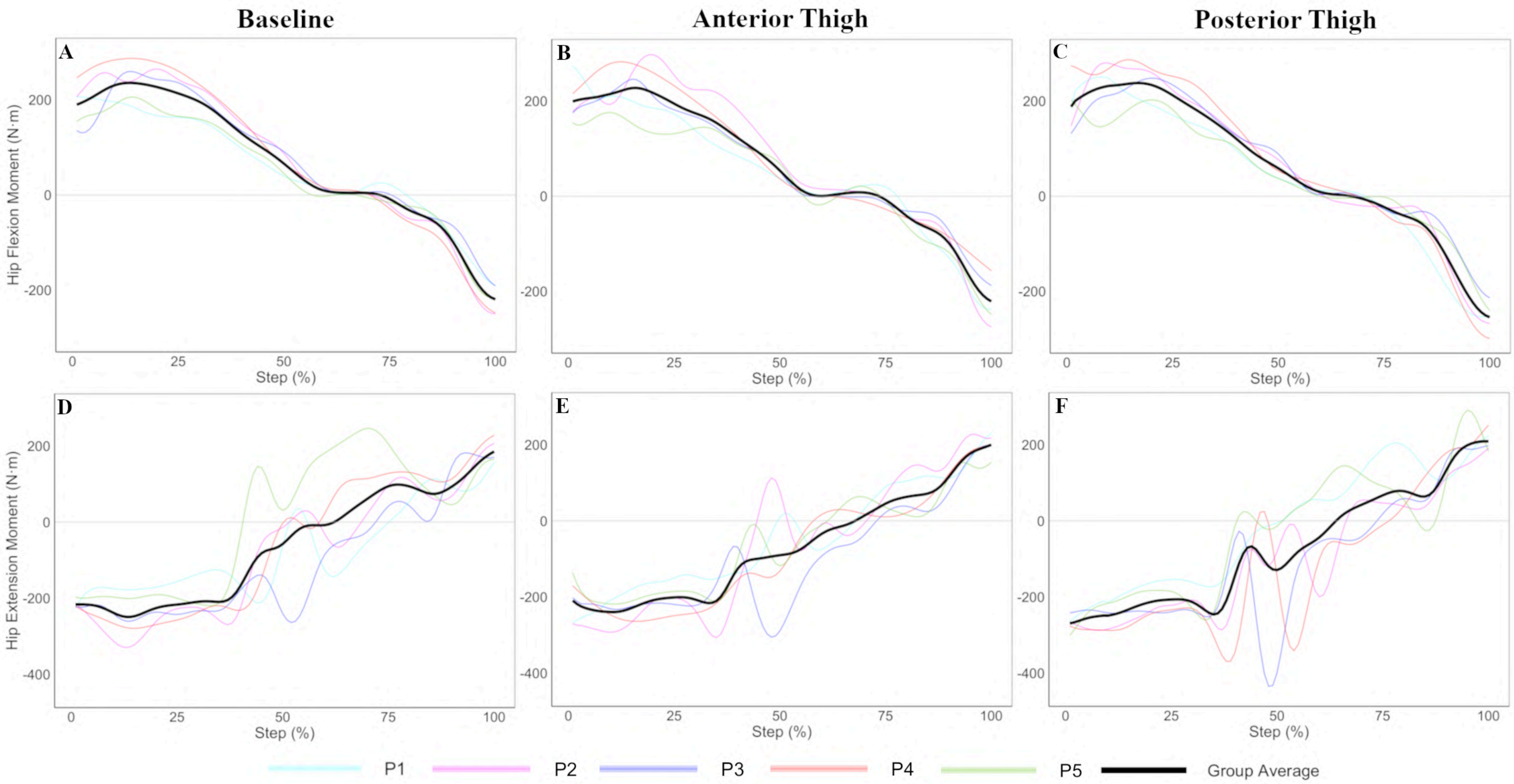
27	Stance knee	Transverse	1.85	Stance ankle	Frontal	2.23
28	Pelvis	Frontal	1.77	Stance knee	Transverse	2.19
29	Swing knee	Transverse	1.72	Stance ankle	Transverse	1.97
30	Thorax	Frontal	1.71	Thorax	Frontal	1.97

Appendix 3 – Chapter 5



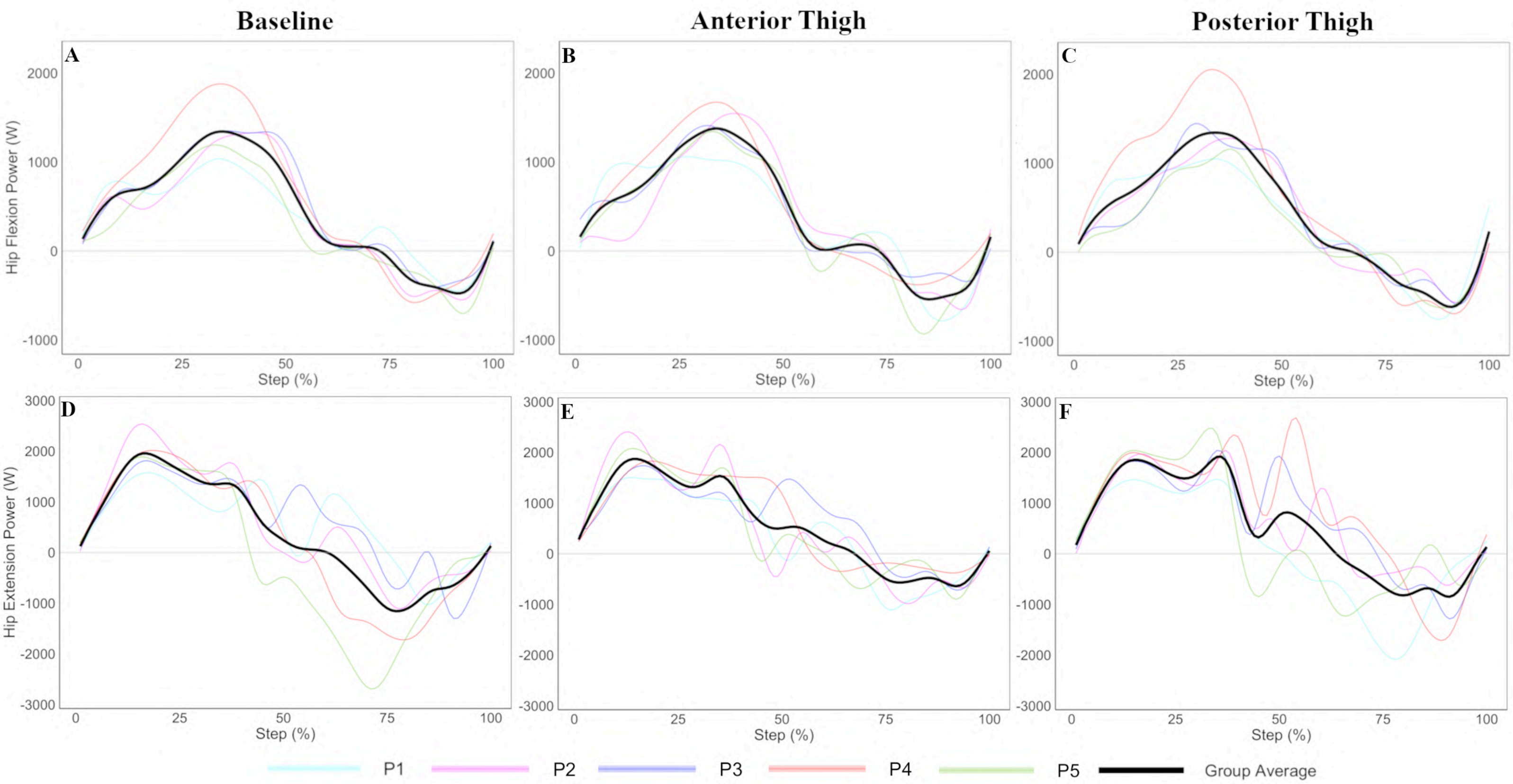
Appendix Figure 3.1 Mean hip flexion and hip extension angular velocity throughout step in baseline, anterior thigh, and posterior thigh WR conditions.

(A) Hip flexion angular velocity at baseline. (B) Hip flexion angular velocity in anterior thigh condition. (C) Hip flexion angular velocity in posterior thigh condition. (D) Hip extension angular velocity at baseline. (E) Hip extension angular velocity in anterior thigh condition. (F) Hip extension angular velocity in posterior thigh condition.



Appendix Figure 3.2 Mean hip flexion and hip extension moment throughout step in baseline, anterior thigh, and posterior thigh WR conditions.

(A) Hip flexion moment at baseline. (B) Hip flexion moment in anterior thigh condition. (C) Hip flexion moment in posterior thigh condition. (D) Hip extension moment at baseline. (E) Hip extension moment in anterior thigh condition. (F) Hip extension moment in posterior thigh condition.



Appendix Figure 3.3 Mean hip flexion and hip extension power throughout step in baseline, anterior thigh, and posterior thigh WR conditions.

(A) Hip flexion power at baseline. (B) Hip flexion power in anterior thigh condition. (C) Hip flexion power in posterior thigh condition. (D) Hip extension power at baseline. (E) Hip extension power in anterior thigh condition. (F) Hip extension power in posterior thigh condition.