Effects of lower limb light-weight wearable resistance on running biomechanics

Journal of Biomechanics 130 (2022) 110903

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech

Effects of lower limb light-weight wearable resistance on running biomechanics

Aglaja Busch [a,b,*], Karl Trounson [c,d], Peter Browne [c,d], Sam Robertson [c]

[a] University Outpatient Clinic, Sports Medicine & Sports Orthopedics, University of Potsdam, Germany
[b] Division of Physiotherapy, Department of Health Professions, Bern University of Applied Sciences, Bern, Switzerland
[c] Institute for Health & Sport, Victoria University, Melbourne, Australia
[d] Western Bulldogs Football Club, Melbourne, Australia

ARTICLE INFO

Keywords:
Kinematic
Kinetic
Weighted running
External loading
3D motion capture

ABSTRACT

Wearable resistance allows individualized loading for sport specific movements and can lead to specific strength adaptations benefiting the athlete. The objective was to determine biomechanical changes during running with lower limb light-weight wearable resistance. Fourteen participants (age: 28 ± 4 years; height: 180 ± 8 cm; body mass: 77 ± 6 kg) wore shorts and calf sleeves of a compression suit allowing attachment of light loads. Participants completed four times two mins 20-m over-ground shuttle running bouts at 3.3 m*s^{-1} alternated by three mins rest. The first running bout was unloaded and the other three bouts were under randomised loaded conditions (1%, 3% and 5% additional loading of the individual body mass). 3D motion cameras and force plates recorded kinematic and kinetic data at the midpoint of each 20-m shuttle. Friedman-test for repeated measures and linear mixed effect model analysis were used to determine differences between the loading conditions (α = 0.05). Increased peak vertical ground reaction force (2.7 N/kg to 2.74 N/kg), ground contact time (0.20 s to 0.21 s) and decreased step length (1.49 m to 1.45 m) were found with additional 5 % body mass loading compared to unloaded running (0.001 > p < 0.007). Marginally more knee flexion and hip extension and less plantarflexion was seen with higher loading. Differences in the assessed parameters were present between each loading condition but accompanied by subject variability. Further studies, also examining long term effects, should be conducted to further inform use of this training tool.

1. Introduction

To enhance physical adaptations in athletes, a number of training modality options exist (Macadam et al., 2017b). One of these is resistance training, which plays an important role in maintaining an athlete's health and regaining strength after injury (Snyder et al., 2009). A recently popularised approach is light-weight wearable resistance (WR), which allows individualised loading in a range of sporting movements (Macadam et al., 2017a). In ballistic athletic movements, the addition of a small mass to a system can give rise to large increases in forces (Hyrosmallis, 2012; Macadam et al., 2017a). The load variability may elicit improved intermuscular coordination which may influence athletic performance and injury prevention (Couture et al., 2020; Hyrosmallis, 2012). Furthermore, light-weight WR may serve as a rehabilitation tool by creating a positive stimulus for tissue remodelling (James et al., 2015). It can also be used during sport-specific movement in the return to activity or play phases. For example, when injured athletes are cleared for running, small loads may elicit an increase in power output, regaining muscle strength and coordination, without overloading the athlete (Snyder et al., 2009). However, monitoring and quantification of possible increases in force are important for practitioners to balance safety and progressive overload. These changes may occur differently with varying loading magnitudes and can affect kinematic and kinetic parameters during different movements, warranting further examination.

Trunk loading via WR during running is well described (Macadam et al., 2017a). It has been shown that loading with >10% of body mass can result in changes to stride frequency, contact time and vertical ground reaction force (GRF) (Silder et al., 2015). Sprinting with WR had been examined in different settings (Macadam et al., 2019;

* Corresponding author at: Am Neuen Palais 10, D-14469 Potsdam, Germany.
E-mail addresses: agbusch@uni-potsdam.de (A. Busch), karl.trounson@live.vu.edu.au (K. Trounson), peter.browne2@live.vu.edu.au (P. Browne), sam.robertson@vu.edu.au (S. Robertson).

https://doi.org/10.1016/j.jbiomech.2021.110903
Accepted 5 December 2021
Available online 9 December 2021

Simperingham and Cronin, 2014). A recent systematic review showed that sprinting with WR loads up to 5% of the individual body mass (BM) affects biomechanical parameters, especially the step frequency and contact time (Feser et al., 2020).

Nonetheless, studies on WR during normal running are limited (Macadam et al., 2017a). Lower limb WR during running varies in literature regarding the placement and load of additional weights to either the foot, ankle or thigh and report inconsistent results (Claremont and Hall, 1988; Couture et al., 2020; Martin, 1985).

Further, literature investigating kinematic parameters during running or walking mostly addresses step variables (e.g. frequency and length) or contact and flight times (Macadam et al., 2017a). Thus, investigations of lower limb angles (hip, knee and ankle) and ground reaction force during running with lower limb WR are necessary, to obtain further knowledge of biomechanical changes and to possibly draw conclusions about specific tissue loading (Trounson et al., 2020).

Therefore, the aim of this study was to investigate the effects of lower limb light-weight WR on kinematic and kinetic parameters while running. It was hypothesised that no significant changes in kinematic and kinetic parameters would be observed during lighter loading conditions (1% and 3% BM) (Couture et al., 2020; Macadam et al., 2017a). It was expected however, that alterations in the assessed parameters during loading would be observed with 5% BM loading, especially at the hip (Couture et al., 2020; Macadam et al., 2017a).

2. Method

2.1. Participants

Fourteen healthy participants (three females) volunteered to participate in the study (age: 28 ± 4 years; height: 180 ± 8 cm; body mass: 77 ± 6 kg). The volunteers had no previous experience with wearable resistance loading of full body, upper or lower limb during running. Participants were excluded if they met any of the following criteria: cardiac, neurological, peripheral and vascular diseases, musculoskeletal disorders, acute infection, acute pain, effusion, other acute lower limb/trunk injuries, thrombosis, alcohol abuse and pregnancy. All participants provided written informed consent prior to the testing. The study followed the latest version of the Declaration of Helsinki and ethical approval was granted by the University Human Research Ethics Committee (HRE19-020).

2.2. Procedure

Anthropometric data was measured and information about the physical activity was assessed by completing the short version of the international physical activity questionnaire (IPAQ-SF) (Craig et al., 2003).

The participants wore compression shorts and calf sleeves (Lila®Exogen™ exoskeleton suit, Sportboleh Sdh Bhd, Kuala Lumpur, Malaysia) allowing attachment of loads (ranging from 50 to 200 g) (Fig. 1). Participants were then prepared for the 3D-motion measurement. The kinematic lower body model consisted of 36 reflective markers placed on the anterior and posterior superior iliac spine, mid-thigh, lateral and medial epicondyles, mid-tibia, medial and lateral malleolus, forefoot on the dorsal aspect on the 2nd metatarsal heads, and on the calcaneus on both the right and left sides according to the Plug-in Gait model (Plug-in-Gait Marker Set, Vicon Peak, Oxford, UK) (Fig. 2) (Trounson et al., 2020).

Participants started with a warm-up and familiarisation of the running task. They ran a 20-m over-ground shuttle run for two minutes at a speed of 2.2 $m*s^{-1}$ and for one minute with the targeted speed of 3.3 $m*s^{-1}$. Following this, the participants completed four trials of the shuttle run interspersed with three minutes rest. Each trial consisted of two minutes, during which the participants ran at 3.3 $m*s^{-1}$ (11.8 $km*h^{-1}$) between two cones. The pace was controlled by a metronome timer. The first running bout was unloaded and the subsequent three bouts under randomised loaded conditions (Fig. 3). The loaded conditions consisted of 1%, 3% and 5% additional loading of the individual BM (Trounson et al., 2020). The load distribution was defined as two thirds on the thigh and one third on the shank (Couture et al., 2020). Hereby, loads were positioned in the middle of the frontal plane and equally distributed. If no equal distribution was possible, heavier parts were placed on the anterior part at the thigh and on the posterior part at the shank. The weight belly was placed proximal to the knee if an unequal distribution occurred.

Kinematic parameters were captured with 10 3D-motion cameras (Vicon MX T40-S, 250 Hz, Vicon, Oxford, UK) focusing on the 10-meter

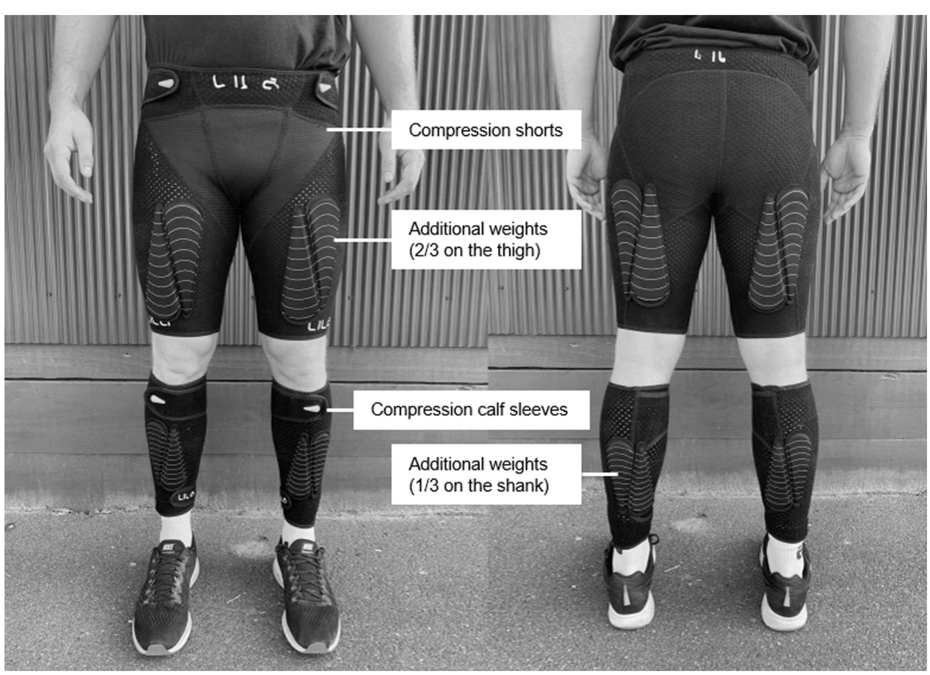

Fig. 1. Compression shorts and calf sleeves (Lila™ Exogen™) with example loading configuration.

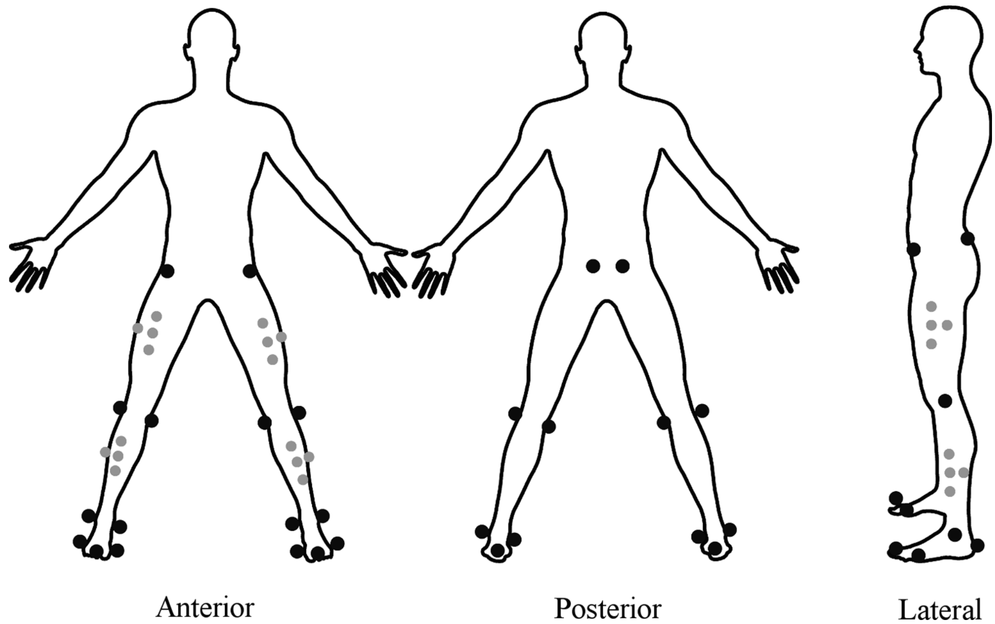

Fig. 2. Lower body Plug-in Gait model. Black dots: anatomical landmarks; grey dots: tracking clusters.

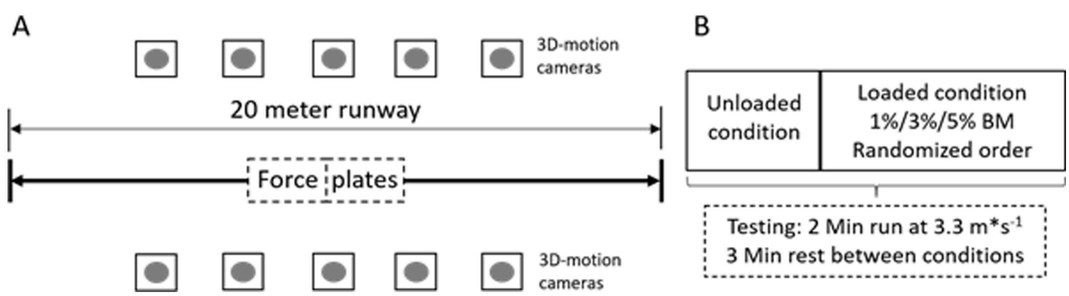

Fig. 3. Schematic representation of study setup and design. A: 20-m runway with two force plates at 10-m and surrounded by 10 3D motion cameras. B: 20-m shuttle running task at different conditions.

mark of the 20-meter runway. Two force plates (AMTI LG6-4, dimensions 1200 mm × 600 mm, 1000 Hz, Advanced Mechanical Technologies Inc., Massachusetts, USA) embedded in the floor in the middle of the runway at 10 m recorded the GRF and were synchronised with 3D motion system. One complete stride cycle was recorded in the capture area each time the participant passed it during the shuttle run. This was predetermined due to technical setup.

After each loaded run participants were asked if they felt running with the loading more difficult than without and if they felt that their running pattern changed with the loading. Possible answers were strongly disagree, disagree, neutral, agree and strongly agree (Lickert, 1932).

2.3. Data processing

Biomechanical data were processed using the software Visual 3D (C-motion Inc., Maryland, USA). Kinematic and kinetic data were simultaneously recorded and temporally aligned in the processing software. Therefore, kinematic parameters could be processed in accordance with certain time points defined by kinetic parameters. Sagittal plane angles of the hip, knee and ankle at initial contact, midstance and take off under all loading conditions were extracted. Upright standing was used to define positive and negative joint angles. Positive joint angles indicated hip flexion, knee flexion and ankle dorsiflexion. Negative joint angles indicated hip extension, knee extension and ankle plantarflexion. Sagittal plane joint angles, ground contact time (GCT) and step length (SL) were low-pass Butterworth filtered at 10 Hz. Further, peak vGRF of one gait cycle per trial was processed using a low-pass Butterworth filter at 120 Hz and normalized to bodyweight.

2.4. Statistical analysis

Statistical analysis was performed using the software SPSS (Version 23.0, IBM, SPSS Inc., Illinois, USA, 2015). Results of the questionnaire are reported as descriptive statistics. The assumption of normal distribution of the biomechanical data was not confirmed by a Shapiro-Wilk test. Non-parametric tests were performed for each variable. A Friedman-test determined if differences under unloaded and the three loaded conditions existed for following variables; peak vGRF, GCT, SL and angles of the hip, knee and ankle at initial contact, midstance and take off. If the test revealed significant difference ($\alpha \leq 0.05$) in the main effect a post-hoc Wilcoxon signed-rank test was performed with additional Bonferroni adjustment to control for type I error ($p = 0.008$). Moreover, Cohens *d* effect sizes were calculated with effect sizes defined as small ($d = 0.2$), medium ($d = 0.5$) and strong ($d = 0.8$) (Cohen, 1988). The data were analysed with non-parametric tests, however, for better comparison with other studies, descriptive statistics are provided in means and standard deviations. Additionally, a linear mixed effect analysis (LMM) fit by restricted maximum likelihood of the relationship between weight conditions and peak vGRF, GCT and SL was performed (R version 4.0, lmer function, package lme4 (Bates and Maechler, 2012)). Loading conditions were entered as fixed effects and subjects as random effects with intercept and random slope.

3. Results

Results of the IPAQ-SF questionnaire showed a moderate (five participants) to high (nine participants) physical activity of the participants. The added weights ranged from 0.62 to 0.87 kg for the 1% BM loading condition, 1.86 – 2.61 kg with additional 3% BM and 3.10 – 4.35 kg with 5% BM.

Questionnaire responses are presented in Table 1.

A significant difference between the loading conditions was found in the peak vGRF ($\chi^2(3) = 15.819$, $p = 0.001$). Post hoc analysis revealed a significant increase during 5% BM loaded running in peak vGRF of 1.5% with medium effect sizes ($Z = -2.707$, $p = 0.007$, $d = 0.5$) compared to unloaded running. Further, a comparison between conditions showed a significant increase in the 3% BM and 5% BM loading ($Z = -3.907$, $p = 0.0001$, $d = 0.6$ and $Z = -3.004$, $p = 0.003$, $d = 0.8$, respectively) compared to 1% BM loaded running (Table 2). Results of the linear mixed effect analysis showed fixed effects estimates with a decrease of > 0.01 N/kg for 1% BM and an increase of 0.01 N/kg for 3% BM and 0.02 N for 5% BM. These effects are negligible, also with regard to larger random effect standard deviations (1% and 3% BM = 0.02 N/kg and 5% BM = 0.03 N/kg). Coefficient plotting revealed no significant difference (Fig. 4).

GCT showed a significant difference between the running conditions ($\chi^2(3) = 16.187$, $p = 0.001$). GCT marginally increased with higher loading, reaching significant differences and a small to medium effect size with 5% BM loading ($Z = -2.706$, $p = 0.007$, $d = 0.4$). Between loading conditions comparisons revealed a significantly higher GCT with 5% BM loading ($Z = -3.033$, $p = 0.002$, $d = 0.4$) against 1% BM loading (Table 2). Fixed effects estimate for 1% BM was -0.001 s, for 3% BM 0.007 s and for 5% BM loading 0.002 s with random effect standard deviation of 0.007 s for 1% BM and 3% BM and 0.006 s for 5% BM. SL decreased over all loaded conditions. 1% BM and 5% BM additional loading showed a significant decrease of 2 to 4 cm ($Z = -2.817$, $p = 0.005$, $d = 0.4$ and $Z = -4.554$, $p = 0.0001$, $d = 0.8$, respectively) compared to unloaded running. Further, SL was significantly decreased during 5% BM ($Z = -3.302$, $p = 0.001$, $d = 0.5$) compared to 3% BM loading (Table 2). LMM fixed effect estimate revealed for 1% BM loading − 0.2 cm, for 3% BM 0.1 cm and 0.4 cm for 5% BM. Random effect standard deviations were 0.4 cm, 0.2 cm, and 0.6 cm for 1% BM, 3% BM and 5% BM, respectively. A significant difference in the coefficients was shown in 5% BM (Fig. 4).

During touchdown more hip flexion was present during loaded running, reaching no significant difference with medium effect sizes compared to unloaded running (3% BM: $Z = -0.695$, $p = 0.487$, $d = 0.5$ and 5% BM: $Z = -1.302$, $p = 0.193$, $d = 0.5$). Comparison between loading conditions showed significantly more flexion during 3% BM ($Z = -2.806$, $p = 0.005$, $d = 0.7$) compared to 1% BM loading. At midstance the hip was significantly less flexed (-1°) with 1% BM loading ($Z = -2.719$, $p = 0.007$, $d = 0.4$). Slightly more flexion was shown in the 3% BM loading ($Z = -0.055$, $p = 0.956$, $d = 0.3$) while 5% BM elicited more extension ($Z = -1.570$, $p = 0.116$, $d = 0.3$) compared to the unloaded condition during midstance. At toe off the hip joint showed a significantly less extension (-0.9°) under 1% BM ($Z = -3.175$, $p = 0.001$, $d = 0.4$) (Table 3).

Table 1
Absolute number of answers given to the questions following each loaded run. Q1: I felt running with the loading more difficult than without. Q2: I felt that my running pattern changed with the loading; 1%, 3% & 5% BM = Body mass.

	1 % BM		*3 % BM*		*5 % BM*	
	Q1	*Q2*	*Q1*	*Q2*	*Q1*	*Q2*
Strongly disagree	5	8	0	1	0	0
Disagree	4	4	1	5	0	3
Neutral	2	1	5	4	0	2
Agree	3	1	7	3	7	5
Strongly agree	0	0	0	0	7	4

Table 2
Normalized peak vertical ground reaction force, contact time and step length during unloaded and loaded running, displayed as mean and standard deviation. Legend: vGRF = vertical ground reaction force; 1%, 3% & 5% BM = added percentage of body mass (loaded condition). * Significant difference to unloaded condition; † Significant difference to 1 % BM; ‡ Significant difference to 3 % BM.

	Unloaded *M ± SD*	**1 % BM** *M ± SD*	**3 % BM** *M ± SD*	**5 % BM** *M ± SD*
Peak vGRF (N/kg)	2.70 ± 0.23	2.69 ± 0.20	2.73 ± 0.24†	2.74 ± 0.22*,†
Contact time (s)	0.208 ± 0.02	0.209 ± 0.02	0.210 ± 0.02	0.212 ± 0.02*,†
Step length (m)	1.49 ± 0.14	1.47 ± 0.13*	1.48 ± 0.13	1.45 ± 0.12*,‡

Flexion of the knee during touchdown was not significantly changed under the loading conditions but showed more flexion with higher loading and medium effect sizes ($0.4 < d > 0.5$). 5% BM loading elicited more knee flexion ($+1.3^\circ$) at midstance without reaching significant difference ($Z = -1.535$, $p = 0.125$, $d = 0.7$) compared to unloaded running. Further, 5% BM loading showed significantly more flexion ($+1.3^\circ$, $Z = -2.943$, $p = 0.003$, $d = 0.7$) compared to the 1% BM loading. At toe off knee flexion was slightly increased ($+0.9^\circ$) with 5% BM loading ($Z = -2.357$, $p = 0.018$, $d = 0.5$) compared to the unloaded condition. Between loaded condition comparison showed a significant increased flexion during 5% BM ($Z = -2.676$, $p = 0.007$, $d = 0.4$) compared to 1% BM loading (Table 3).

The ankle at touchdown showed no significant changes between all condition ($\chi^2(3) = 2.979$, $p = 0.395$) and effect sizes were small ($0.01 \leq d \geq 0.2$). Ankle dorsiflexion at midstance was steadily increased with higher loading ($Z = -1.813$, $p = 0.07$, $d = 0.3$ for 1% BM and $Z = -2.478$, $p = 0.013$, $d = 0.5$ for 3% BM) reaching statistical significance with 5% BM loading ($Z = -2.784$, $p = 0.005$, $d = 0.5$). At toe off additional loading elicited no significant changes compared to unloaded running. Further, a significantly decreased plantarflexion was found in 5% BM ($Z = -3.086$, $p = 0.002$, $d = 0.5$) compared to 1% BM loading (Table 3).

4. Discussion

This study compared kinematic and kinetic parameters during running with additional lower limb loading of 1%, 3% and 5% of the individual body mass to an unloaded condition. It was hypothesised that significant changes would be seen with 5% loadings. This hypothesis could not be confirmed in all assessed parameters. Results showed increases in peak vGRF and GCT along with a decrease in SL during running with additional 5% BM compared with unloaded and 1% BM running. Differences in the joint angle occurred mainly comparing unloaded running and 1% and 5% BM loading and were different between individual joints and gait phases.

Medium effect size differences in GCT and SL were mainly found with loadings of 5% BM. The effects of higher loading shown by the coefficient plots underline that changes more likely due to the additional loading. However, random effect standard deviations exceeding the fixed effect estimates point to a non-negligible variation between the subjects.

The slightly higher GCT and decreased SL during 5% BM loading compared to unloaded running are not consistent with findings in the published literature (Claremont and Hall, 1988; Martin, 1985). Changes in biomechanical parameters have been examined during treadmill running at a speed of 3.3 $m{*}s^{-1}$ with loading on the thigh and feet (Martin, 1985). Modest changes were found in increased stride length, swing time and flight time during running with 1 kg additional feet

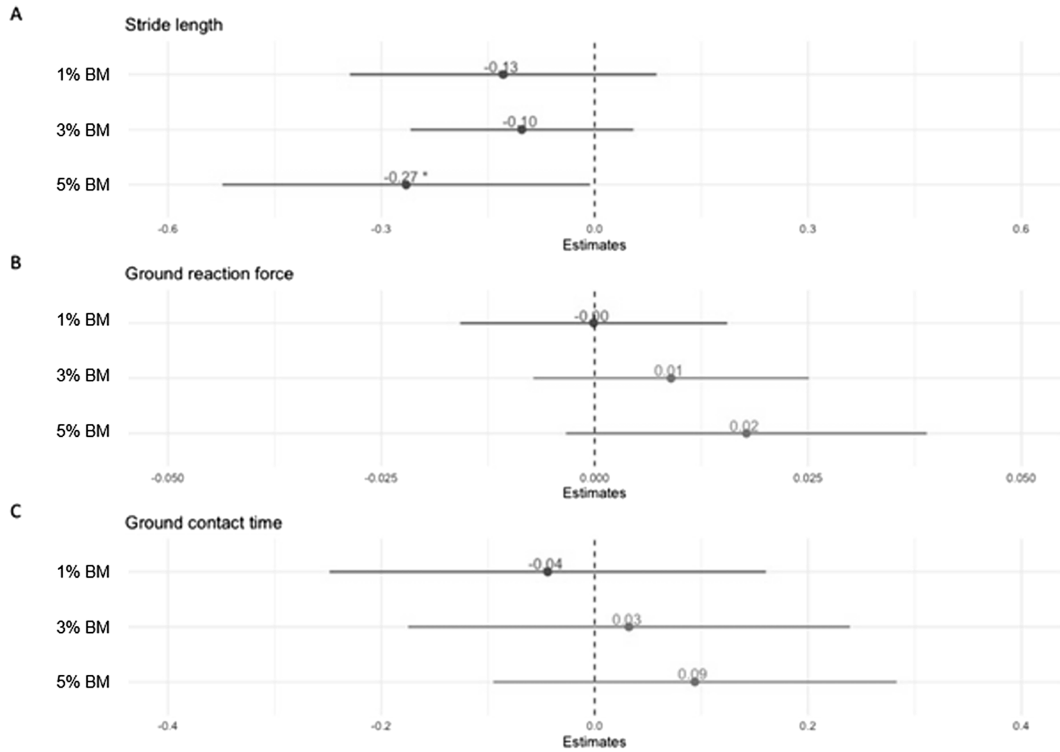

Fig. 4. Linear mixed effect model coefficient plots of A: Stride length, B: Ground reaction force and C: Ground contact time over the weighted running conditions. Legend: 1%, 3% & 5% BM = added percentage of body mass (loaded condition) Showing the mean and 95% confidence interval. * indicates significant difference compared to unloaded condition.

Table 3
Angular changes of hip, knee and ankle during running with and without loading. Positive values represent hip flexion, knee flexion and ankle dorsiflexion, while negative values represent hip extension, knee extension and ankle plantarflexion. Legend: TD: Touchdown; MS: Midstance; TO: Toe off; UL = Unloaded condition; 1%, 3% & 5% BM = Body mass; M: mean; SD: Standard deviation. * Significant difference to unloaded condition; † Significant difference to 1 % BM.

	UL *M ± SD*	1 % BM *M ± SD*	3 % BM *M ± SD*	5 % BM *M ± SD*
Hip TD (°)	28.7 ± 6.6	28.4 ± 4.7	29.5 ± 5.3†	29.4 ± 5.7
Hip MS (°)	11.7 ± 5.5	10.7 ± 5.1*	11.7 ± 4.3†	10.8 ± 4.4
Hip TO (°)	−15.4 ± 5.7	−16.3 ± 5*	−15.3 ± 5.2	−16.2 ± 5.8
Knee TD (°)	10.1 ± 5.2	10.2 ± 5.4	11.0 ± 4.9	11.0 ± 5.2
Knee MS (°)	34 ± 5.6	34 ± 5.2	34.7 ± 4.5	35.3 ± 4.7†
Knee TO (°)	5.8 ± 5.2	6.0 ± 5.1	6.1 ± 5.2	6.9 ± 5.4†
Ankle TD (°)	−9.6 ± 7.1	−10 ± 7.2	−9.9 ± 7.4	−9.5 ± 7.2
Ankle MS (°)	9.6 ± 3.8	10 ± 3.6	10.3 ± 3.5	10.3 ± 3.7*
Ankle TO (°)	−36.3 ± 7	−36.5 ± 6.8	−36.2 ± 7.4	−35.1 ± 7.5†

loading (approximately 1.38% BM) (Martin, 1985). Another study reported no changes in step variables and swing time during treadmill running (2.5 to 3.8 m*s^{-1}) with 0.45 to 0.9 kg hand held loading, attachment to the ankle or both combined (Claremont and Hall, 1988). These differences compared to this study may be due to the various distribution of loads. For a better comparison and evidence-based results future studies should try to follow the same load distribution (Macadam et al., 2017a). Moreover, there is an ongoing discussion about differences in treadmill and over-ground running depending on measured variables and running velocities (Miller et al., 2019). Therefore, comparisons of the current results and studies with treadmill running need to be handled with caution and kept in mind while applying weighted running.

Furthermore, it is discussed by Martin (1985) that changes during foot loading and not during thigh loading might have been due to greater moment of inertia at the hip joint (Martin, 1985). Results of the present study support this explanation given the observed increased hip flexion during touchdown with higher loading.

In the literature kinematic parameters during weighted running are generally limited to step variables and contact or flight times. Therefore, a direct comparison of the assessed joint angle parameters in the present study is difficult (Couture et al., 2020; Cross et al., 2014). However, it has been stated that less leg extension at toe off is beneficial for the running economy (Moore, 2016). Results showed marginally more knee flexion and hip extension, and less plantarflexion with higher loading. The kinematic changes may reflect a coping strategy to maintain a good running economy with higher loading and is further debated in the discussion of the kinetic parameters, in the following paragraph. This study, in contrast to the existing literature, highlights joint angle changes next to other kinematic parameters, but only at specific time point during the stance phase. Future studies may additionally examine angular changes during the swing phase to gain more knowledge of possible alterations in the open kinetic chain.

Kinetic assessment showed a small increase in peak vGRF during loaded running with 3% and 5% BM compared to 1% BM and unloaded running. Furthermore, effect estimates of weight were relatively small while subject variability expressed by the random effect standard deviations was higher. In the literature results of kinetic evaluations in trained male runners during treadmill running at a velocity of 3.9 m*s^{-1} with lower limb loading of 1%, 3% and 5% BM using WR have been reported (Couture et al., 2020). Functional vGRF was slightly higher but not significantly greater compared to unloaded condition. Effective peak vGRF decreased with higher loading from 1% to 5% BM and was smaller compared to the unloaded condition. In contrast, another study presented kinetic parameters during sprint running with 5% BM on a treadmill using the same compression suit (Simperingham and Cronin, 2014). They found a significant increase in mean vGRF in the acceleration phase and during maximum velocity compared to unloaded running (Simperingham and Cronin, 2014). Those results are in line with the current findings of a significant increase in peak vGRF during running with 5% BM loading. Nonetheless, both studies report less increase in vGRF than the magnitude of added mass, which is consistent with results of the present study (Couture et al., 2020; Simperingham and Cronin, 2014).

In the present study running with light-weight WR did elicit significant changes on a group-level basis in some of the examined kinematic and kinetic parameters. The additional linear mixed effect model analysis accounting for participant variability emphasised a more individual approach when transferring the results to the training context and need to be kept in mind when applying in-field prescriptions. Despite some kinetic and kinematic parameters reaching significant difference, with higher loading the reported small to medium effect sizes question the clinical relevance. Small magnitudes of the changes (<5%) might lay within the individual variability (Macadam et al., 2017b). Therefore, the practical implications of these findings and goal directed approaches from the different parts (e.g. strength and conditioning coach or physio) of the relevant supportive staff needs to be considered. It has been reported that distal load placement at the lower limb elicits a rotational overload with increased inertia (Martin, 1985). The lack of changes in the assessed biomechanical parameters may be due to the light loading aligned with the body proportions and relative segment weights, as studies have shown differences in biomechanical parameters with loadings higher than 5% BM (Macadam et al., 2017a). Other studies support the theory of acute neuromuscular alterations elicited by the additional loading. It is hypothesised that an increased muscular output exists before gait pattern changes can develop. Internal forces applied by the muscles on the bones and joints might be higher and is reflected in ground reaction forces (Couture et al., 2020; James et al., 2015). This hypothesis is supported by the subjective perceptions of the participants with more difficulty to run and changes of running pattern with higher loading. To further quantify this perception and prove the stated hypothesis, future studies should examine the neuromuscular activity during loaded running e.g. with electromyography (Häkkinen et al., 2001). Moreover, studies have shown higher energy consumption during loaded running without changes of mechanical parameters (Claremont and Hall, 1988; Macadam et al., 2017a; Martin, 1985). This supports the aforementioned hypothesis and must be kept in mind for goal directed training.

Efficient running economy is associated with shorter stride length, greater maximal plantarflexion velocity and lower knee flexion velocity during swing time, less leg extension during toe off and smaller total vertical GRF (Anderson, 1996; Heise and Martin, 2001; Moore, 2016). Results of this study found slightly decreased SL and more flexion in knee and ankle during toe off with higher loading might be an indication of maintaining the running economy while additional loading is applied. Of note are the increases in knee flexion and plantarflexion at toe off and less peak vGRF during loading with 5% BM compared to 1% BM. However, advantages and drawbacks of different loading conditions need to be examined in longitudinal intervention studies.

None of the participants had trained with the compression suit before but reported a moderate to high physical activity. It may be that regular sporting performance with light fatigued conditions during training or competitions could trigger compensatory strategies to maintain a certain standard of the performance (Macadam et al., 2017a). This could explain the minor biomechanical changes in the present study. Responses in untrained persons may be different, requiring further examination.

The study was performed based on already used procedures and recommendations of the literature (Couture et al., 2020). Nonetheless, the following limitations need to be considered. The warm-up and familiarization to the running task and speed might have been too short and were completed without resistance. Therefore, the effects of weighted running could change with longer running periods and familiarisation. Nonetheless, the short warm-up, randomisation and running bouts of 2 min were selected to diminish possible fatigue and learning effects. Although kinematic markers were attached with tape, loss during running could not be prevented. Lost markers were rebuilt using the mentioned programs of the software but will not be as accurate as the original body marker. Further, not all stride cycles per participant and condition could be used in the analysis due to technological setup. Potential higher variability over more stride cycles is possible and need to be considered when these outcomes are compared with other studies. The time to reach the end of the 20-m track was given auditorily, however, running speeds may vary due to the turning at the end of the track and might be influenced by hearing of the remaining lap time. Nonetheless, velocity variations are present during training without the use of technical equipment as well and represent real life conditions. Furthermore, analysis of discrete parameters at certain time points dismisses large parts of the full gait cycle. Future studies should evaluate biomechanical parameters during the whole gait cycle to draw relevant conclusions on possible effects (Phinyomark et al., 2018; Trounson et al., 2020).

WR allows athletes to train with a great range of motion and in a sport specific context. The compression shorts and calf sleeves used allowed attachment of light loads which were set at additional loading of 1%, 3% and 5% of the individual body mass. Light-weight WR on the lower limbs showed changes in some of the assessed biomechanical parameters during running, especially with 5% BM loading supported by medium effect sizes. The results are consistent with findings of the current literature and give rise to further research questions. In particular, the evaluation of neuromuscular adaptations, which might underlie the small changes in biomechanical parameters with light loads, should be considered in future studies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors would like to thank Neil French Collier for his statistical advice and all the participants for their contribution to this study.

References

Anderson, T., 1996. Biomechanics and running economy. Sport. Med. 22 (2), 76–89. https://doi.org/10.2165/00007256-199622020-00003.

Bates, D., Maechler, M., Bolker, B., 2012. lme4: Linear Mixed-Effects Models Using S4 classes.

Claremont, A.D., Hall, S.J., 1988. Effects of extremity loading upon energy expenditure and running mechanics. Med. Sci. Sports Exerc. 20 (2), 167–171. https://doi.org/10.1249/00005768-198820020-00011.

Cohen, J., 1988. Statistical Power Analysis for the Behavioral Sciences, second ed. Erlbaum, Hillsdale, NJ.

Couture, G.A., Simperingham, K.D., Cronin, J.B., Lorimer, A.V., Kilding, A.E., Macadam, P., 2020. Effects of upper and lower body wearable resistance on spatio-temporal and kinetic parameters during running. Sport. Biomech. 19 (5), 633–651. https://doi.org/10.1080/14763141.2018.1508490.

Craig, C.L., Marshall, A.L., Sjostrom, M., Bauman, A.E., Booth, M.L., Ainsworth, B.E., Pratt, M., Ekelund, U., Yngve, A., Sallis, J.F., Oja, P., 2003. International physical activity questionnaire: 12-country reliability and validity. Med. Sci. Sports Exerc. 35, 1381–1395. https://doi.org/10.1249/01.MSS.0000078924.61453.

Cross, M., Brughelli, M.E., Cronin, J.B., 2014. Effects of vest loading on sprint kinetics and kinematics. J. Strength Cond. Res. 28, 1867–1874. https://doi.org/10.1519/JSC.0000000000000354.

Feser, E.H., Macadam, P., Cronin, J.B., Feser, E.H., 2020. The effects of lower limb wearable resistance on sprint running performance: a systematic review. Eur. J. Sport Sci. 20, 394–406. https://doi.org/10.1080/17461391.2019.1629631.

Häkkinen, K., Kraemer, W.J., Newton, R.U., Alen, M., 2001. Changes in electromyographic activity, muscle fibre and force production characteristics during heavy resistance/power strength training in middle-aged and older men and women. Acta Physiol. Scand. 171, 51–62. https://doi.org/10.1046/j.1365-201X.2001.00781.x.

Heise, G.D., Martin, P.E., 2001. Are variations in running economy in humans associated with ground reaction force characteristics? Eur. J. Appl. Physiol. 84 (5), 438–442. https://doi.org/10.1007/s004210100394.

Hyrosmallis, C., 2012. The effectiveness of resisted movement training on sprinting and jumping performance. J. strength Cond. Res. 26, 299–306. https://doi.org/10.1519/JSC.0b013e3182185186.

James, C.R., Atkins, L.T., Yang, H.S., Dufek, J.S., Bates, B.T., 2015. Kinematic and ground reaction force accommodation during weighted walking. Hum. Mov. Sci. 44, 327–337. https://doi.org/10.1016/j.humov.2015.10.004.

Lickert, R., 1932. A technique for the measurement of attitudes. Arch. Psychol. 22, 1–55.

Macadam, P., Cronin, J.B., Simperingham, K.D., 2017a. The effects of wearable resistance training on metabolic, kinematic and kinetic variables during walking, running, sprint running and jumping: a systematic review. Sport. Med. 47 (5), 887–906. https://doi.org/10.1007/s40279-016-0622-x.

Macadam, P., Simperingham, K.D., Cronin, J.B., 2017b. Acute kinematic and kinetic adaptations to wearable resistance during sprint acceleration. J. Strength Cond. Res. 31, 1297–1304.

Macadam, P., Simperingham, K.D., Cronin, J.B., 2019. Forearm wearable resistance effects on sprint kinematics and kinetics. J. Sci. Med. Sport 22 (3), 348–352. https://doi.org/10.1016/j.jsams.2018.08.012.

Martin, P.E., 1985. Mechanical and physiological responses to lower extremity loading during running. Med. Sci. Sports Exerc.

Miller, J.R., Van Hooren, B., Bishop, C., Buckley, J.D., Willy, R.W., Fuller, J.T., 2019. A systematic review and meta-analysis of crossover studies comparing physiological, perceptual and performance measures between treadmill and overground running. Sport. Med. 49, 763–782. doi: 10.1007/s40279-019-01087-9.

Moore, I.S., 2016. Is there an economical running technique? A review of modifiable biomechanical factors affecting running economy. Sport. Med. 46 (6), 793–807. https://doi.org/10.1007/s40279-016-0474-4.

Phinyomark, A., Petri, G., Ibáñez-Marcelo, E., Osis, S.T., Ferber, R., 2018. Analysis of big data in gait biomechanics: current trends and future directions. J. Med. Biol. Eng. 38 (2), 244–260. https://doi.org/10.1007/s40846-017-0297-2.

Silder, A., Besier, T., Delp, S.L., 2015. Running with load increases leg stiffness. J. Biomech. 48, 1003–1008. https://doi.org/10.1016/j.jbiomech.2015.01.051.Running.

Simperingham, K.D., Cronin, J.B., 2014. Changes in sprint kinematics and kinetics with upper body loading and lower body loading using exogen exoskeletons: a pilot study. J. Aust. Strength Cond 22, 69–72.

Snyder, K.R., Earl, J.E., O'Connor, K.M., Ebersole, K.T., 2009. Resistance training is accompanied by increases in hip strength and changes in lower extremity biomechanics during running. Clin. Biomech. 24 (1), 26–34. https://doi.org/10.1016/j.clinbiomech.2008.09.009.

Trounson, K.M., Busch, A., Collier, N.F., Robertson, S., 2020. Effects of acute wearable resistance loading on overground running lower body kinematics. PLoS One 15, 1–19. doi: 10.1371/journal.pone.0244361.