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Consensus paper on testing and evaluation of military exoskeletons for the dismounted combatant

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ABSTRACT

Enhancing the capabilities of the dismounted combatant has been an enduring goal of international military research communities. Emerging developments in exoskeleton technology offers the potential to augment the dismounted combatant's capabilities. However, the ability to determine the value proposition of an exoskeleton in a military context is difficult due to the variety of methods and metrics used to evaluate previous devices. The aim of this paper was to present a standard framework for the evaluation and assessment of exoskeletons for use in the military. A structured and systematic methodology was developed from the end-user perspective and progresses from controlled laboratory conditions (Stage A), to simulated movements specific to the dismounted combatant (Stage B), and real-world military specific tasks (Stage C). A standard set of objective and subjective metrics were described to ensure a holistic assessment on the human response to wearing the exoskeleton and the device's mechanical performance during each stage. A standardised methodology will ensure further advancement of exoskeleton technology and support improved international collaboration across research and industry groups. In doing so, this better enables international military groups to evaluate a system's potential, with the hope of accelerating the maturity and ultimately the fielding of devices to augment the dismounted close combatant and small team capability.

1. Introduction

The dismounted combatant is required to carry loads in excess of 80–100% of their body mass over a variety of difficult and complex terrains.[1–3] In response to the added mass there is a decreased time to fatigue[4] and increased prevalence of overuse or chronic musculoskeletal injuries.[2] The dismounted combatant takes a direct part in the hostilities of an armed conflict, thus reducing the negative impacts of load carriage and enhancing their capability during warfare has been an enduring goal. The North Atlantic Treaty Organization (NATO) has identified and defined five key capability areas for the dismounted close combatant: mobility, lethality, survivability, sustainability and C4I (Command, Control, Communications, Computers and Intelligence). Exoskeletons designed to augment the mobility capabilities during load carriage would allow the dismounted combatant to more easily traverse through any kind of complex terrain and thereby extend their geographic sphere of influence.

An exoskeleton, defined here as a body-worn mechanical device that works in parallel with the user,[5] has the potential to enhance mobility. Current exoskeletons can be classified according to their various power states (active or passive) and structures (hard or soft). Active exoskeletons[6,7] describe devices that require a power source, whereas passive devices[8,9] have no external power and typically utilise springs or serve as an external support. Further, the structure of the device may include hard rigid components such as aluminium or carbon fibre,[10–12] soft textile or cable components,[6,13] or a combination of both. Recent developmental efforts have yielded devices that reduced metabolic cost by up to 15%[6–8] or potentially minimised injury risk by offsetting the external load outside the musculoskeletal system[10,14,15] during common military tasks such as walking and load carriage. While

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reducing the metabolic cost of walking and the potential for injury are highly important, equally important may be the ability of exoskeletons to improve both the physical and cognitive capacity of the individual dismounted combatant, as well as the effectiveness of a combat unit as a whole.

Over the previous decade, there has been an exponential increase in the number of available exoskeletons on the market.[5,16,17] There has also been a concurrent increase in the number of scientific evaluations involving human volunteers performed internationally by academic and government laboratories. For example, evaluations have recently been conducted for the OX,[18] Exo Hiker,[10,11] Warrior Web,[6] B-Temia[19] and MIT ankle exoskeleton.[7,12] Many publications pertaining to current military-specific exoskeletons have focused on a single activity or task such as steady state walking or running. Further, these assessments were generally completed on an instrumented treadmill[6,8,10] or overground,[15,19,20] with few devices being tested in multiple evaluations or during military specific exercises. Though common assessment tasks have been employed, a wide range of different metrics and methods used to evaluate devices has been reported.

The importance of developing standard assessment and evaluation metrics for specific exoskeleton applications has been recently highlighted.[21] In line with this suggestion, an initial set of basic and applied military specific tasks for assessing lower body exoskeletons has been developed by Carlson et al.[22] The authors[22] provided a readily accessible methodology that was low cost, and intended as a high-level assessment to inform initial designs and concepts. As such, the methods described did not include details of task parameters or objective and subjective metrics, as has been recommended by Torricelli et al.[21] Therefore, the absence of traditional laboratory measurements significantly reduces the scientific rigour and reliability of the potential findings from the tasks described by Carlson et al.[22]

Transparency in the literature regarding design details and the effect of the device on human performance will expedite the rate at which technology matures, the likelihood of such products being fielded[23] and the military impact of this new technology. As such, in addition to in-house testing, independent and impartial evaluations offer an unbiased insight into a device's performance, shortcomings and potential use cases/applications. The development and consensus of a progressive, staged methodology will ensure suitable methods, protocols and metrics are employed as a baseline standard for the assessment of military exoskeletons during in-house testing and independent evaluations. This would make comparisons between different devices, control systems, materials, and refined versions of a system possible. Further, the value proposition of a device(s) can then be adequately determined across various military relevant situations and requirements to help determine a potential use case for the device (Fig. 1).

The aim of this paper was to present a standard framework for the evaluation and assessment of exoskeletons for use in the military. A structured and systematic methodology that enables a range of exoskeleton systems to be evaluated through a progressive set of activities that relate to the dismounted close combatant is presented (Fig. 2). We are sharing our standardised framework in the hope that in doing so will help the exoskeleton community objectively evaluate individual systems while producing meaningful results that may be comparable, generalizable, and applicable to the development of future exoskeleton systems.

2. Assessment and evaluation methodologies

Human-in-the-loop evaluations must entail a holistic approach, with standardised assessments ranging from controlled laboratory tests to the real-world military context, using both objective and subjective measurement tools. Further, testing methodologies should be developed from the end-user perspective and remain agnostic to a particular device. This approach will permit any device to utilise the staged assessment methodology, regardless of the design and functional characteristics. The value proposition of a device can then be adequately determined across various military relevant situations and tasks to help determine its optimal use-case(s). Additionally, utilisation of a standard protocol in assessing these technologies can enable "fair" comparisons between various exoskeleton systems.

The presented testing methodology is to be completed as an iterative process (Stages A–C; Fig. 2), structured to progress from simple, controlled laboratory measurements to more complex, real-world military specific tasks and duties.[21] The progression of activities is such that negative outcomes found at a particular stage can be provided to the system designers so that the exoskeleton design can be changed before the next iteration of the study. By including a variety of tasks in the assessment, those activities that the device may augment and those for which it imposes a cost can be highlighted and identified. This approach minimises participant risk and provides an opportunity to complete an integrated evaluation process where the device can be further refined by the developers dependent on early findings.

The development of military specific testing recommendations should consider key mobility categories required of the dismounted combatant. Specific tasks, duration, and level of physical effort may be highly varied across these categories. For instance, in the case of the dismounted close combatant these activities included, (i) tactical or approach marches (prolonged moderate intensity, i.e. march); (ii) moving tactically but not in an engagement (prolonged moderate intensity, i.e. advance, patrol, urban clearance, obstacle negotiation); (iii) moving tactically while engaged (intermittent high intensity, i.e. fire and movement, obstacle negotiation); (iv) manual material handling (prolonged moderate intensity, i.e. movement of material within a base, stretcher carry); and (v) ingress/egress (low intensity, i.e. fixed/rotary wing, ground transport, maritime). It is critical that a variety of tasks be included in the assessment protocol to encompass the full range of movement patterns, muscle groups and energy systems associated with dismounted operations.

For a specific task, the completed conditions should include a *control* (no device), *exoskeleton ON* (device worn and active) and *exoskeleton OFF* (device worn and inactive). The exoskeleton ON condition characterises the performance of the device (relative to the control), and the exoskeleton OFF condition sets the baseline for the burden or penalty of wearing the device (relative to the control). Test conditions should be randomised or counterbalanced across participants to minimise any order effect.

Participants should have sufficient military experience relevant to the assessable outcomes, no current or recent musculoskeletal injuries and cleared for full duties. Combat relevant clothing (i.e. helmet, boots, armour and weapon) should be worn and the type and mass of the backpack consistent throughout all conditions, and equivalent to relevant combat loads (i.e. standard patrol order (∼20 kg) or marching order (∼35 kg)). Although it should be noted that as technology continues to progress some exoskeletons might change the standard dismounted combatant's combat ensemble, and as such, these configurations should be considered when making comparisons. Further, it is imperative the device is correctly fitted, comfortable for the user, and software algorithms adjusted to suit the task and the user's characteristics (e.g., anthropometry, gait pattern, etc.).

Familiarisation sessions must be completed prior to testing to ensure the user has sufficiently adapted to wearing the device. Previous research has demonstrated 1–2 familiarisation sessions of approximately 15–24 min each to adapt to a powered and passive

Warfighter performance →

Warfighter capabilities ↓

	Current work load/rate	Reduced work load/rate	Substantially reduced work-load/work-rate
Current capabilities	Baseline	Core competency	Core competency
Improved current capabilities	Core competency	Core competency	Advanced
Improved current capabilities and additional capabilities provided	Advanced	Transformational	Transformational

Fig. 1. A presented value proposition framework for military exoskeleton systems for a given task or set of tasks. Baseline is defined as a system that is able to overcome the burden imposed on the user by simply wearing the device and does not impose any new penalties on the user. Core competency defines a system that is optimising existing capabilities. Advanced highlights a system that expands from existing capabilities. Transformational implies a device that allows a substantial improvement in current performance and enables the completion of new capabilities that were not previously possible.

exoskeleton.[6,8,24] The total number and duration of familiarisation sessions required may vary between devices (active or passive), design (whole body, upper body, lower limb with multiple joints or single joint) and control schemes (EMG, kinematic, force-based, or none). As a guide, identifying a plateau or diminishing returns in a key metric of interest (e.g., oxygen consumption or EMG) within and between consecutive sessions serves as an indicator of a participant's familiarisation status.[24,25]

A sample size of 6–10 participants is common amongst previous research.[25–27] Participant factors including demographics, strength and fitness, and unencumbered anthropometry that are relevant to the device to be tested should be characterised. A minimum set of recommended metrics include:

- Demographic information — age, sex, handedness (shooting, writing and/or eye dominance), rank, role(s), trade, length of service and/or operational experience.
- Strength and fitness — maximal aerobic capacity via an acceptable test such as a VO2max test, multi-stage fitness test or 2-mile run time[28,29] and leg power via a vertical jump test.
- Unencumbered anthropometry — stature, body mass, segment lengths (e.g. arm, leg or trunk lengths), breadths (e.g. waist, shoulder or acromion breadth), circumferences (e.g. arm, hip, waist and chest) and skinfold thickness (e.g. seven-site formula[30]; abdominal, triceps, chest, midaxillary, subscapular, suprailiac and thigh).[30–32]

Stage A is to be completed under laboratory conditions to assess device impacts on the performance of controlled tasks (Table 1). While less mission specific, this stage assesses the device through a range of foundational movements to understand the basic impact a device has on soldier mobility. Treadmill and overground laboratory locomotion trials provide large, reliable sets of data on human and exoskeleton performance. To provide a holistic evaluation of the device a range of objective and subjective metrics can be collected (Table 1).

Functional movement tests will evaluate basic movement patterns including range of motion, stepping over obstacles, static balance, movement between firing positions, handling firearms or relevant tools and donning/doffing the exoskeleton. The functional movement tests are to be completed in a controlled laboratory environment, tailored to the specific device under evaluation and in positions the user would be expected to achieve. It is essential these tests are completed prior to any dynamic tests to ensure safety of the participant and identify any limitations or risks with the device.

Laboratory locomotion trials can be completed on a treadmill and overground for a minimum duration of 5 min each trial to allow the user to reach steady state oxygen consumption. Speeds should be representative of key tasks and guided by subject matter experts, such as patrolling, marching, running and/or user self-selected speeds. Treadmill locomotion trials can be performed on a level, inclined, and declined grade. Overground trials should be performed on a standardised flat surface to ensure a steady pace throughout the walking duration.

The use of exoskeletons may offset decreases in cognitive performance associated with load carriage. Cognitive tasks relevant to the missions of the dismounted combatant need to be examined during loaded marching, such as navigation, target identification, communication, marksmanship and reaction time and accuracy.[33,34] These tasks could be completed under both fatigued and non-fatigued conditions.

Stage B is intended to simulate movements that are specific to the dismounted combatant, improving specificity and relevance to the end-user (Table 1). The activities completed in Stage B will require multiple movement transitions, assessing the devices' ability to adapt to changes in posture and tasks performed. Standardised assessments including tests used by an Armed Service for the selection and retention of the dismounted close combatant and standard military obstacle courses such as the load effects assessment program (LEAP)[35] are recommended. Whilst tasks are simulated, participants can be fully instrumented during these assessments to obtain objective measurements in the field on the devices impact on soldier mobility, lethality, sustainability and survivability.

Standardised assessments specific to the dismounted close combatant are to be completed according to defined protocols. For example, the Australian Physical Employment Standards Assessment (PESA) and Canadian FORCE evaluation[36] include tasks such as a forced march, tactical movement test, and manual material handling assessments to assess soldier mobility and sustainability.

The LEAP is an instrumented obstacle and combat effectiveness course designed to replicate movement patterns regularly performed by Army personnel to assess soldier mobility and survivability.[35] The entire LEAP course can be completed or a

Table 1
An example of AUS specific test methodologies, including suggested task descriptions, applications, and key metrics to be assessed for each stage.

Task		Task description	Application Lab (L)/Field (F)	Metrics
Stage A				
Functional movement tests		Joint range of motion Movement between operational tasks (prone/crouched/seated/standing upright) Movement between firing positions (prone to taking-a-knee to upright) Crawling and stepping over obstacles Static balance	L/F	EMG Kinetics Kinematics Questionnaire RPE Time to complete
Walking/running		7–10 min duration $0.55\ \text{m s}^{-1}$ and/or $1.39\ \text{m s}^{-1}$ and/or $2.08\ \text{m s}^{-1}$ 0%, 10% and/or −10% grade	L—treadmill & overground	Cardiovascular EMG Spatiotemporal Kinetics (GRF, insole, exo)[a] Kinematics Questionnaire RPE Cognitive
Stage B				
Dismounted combatant employment standards	Forced march test	15 km forced paced march ($5.5\ \text{km h}^{-1}$), completed between 150–165 min, wearing a marching order (40–45 kg)	F	Cardiovascular EMG Spatiotemporal
	Tactical movement test	1 km move (8 min), 16 × 6 m bounds (20 s bounds), 18 m leopard crawl (35 s)	F	Kinetics (insole) Kinematics
	Manual handling	2 × 22 kg jerry cans/kettle bells for 11 × 25 m legs (5 s rest between legs); Lift a 35 kg box from the ground to a 1.5 m platform then lower back to ground	L/F	Questionnaire RPE
AUS-LEAP [35,a]		Tunnel and hatch Sprint Stair and ladder Agility run Casualty drag Window clearance Bounding rushes Balance beam Low crawl Courtyard walls Manual handling (horizontal & vertical weight transfer) Vertical jump	L/F	Obstacle completion time Cardiovascular EMG Spatiotemporal Kinetics (FP, insole) Kinematics Questionnaire RPE
Marksmanship assessment		Static—simulated/range marksmanship assessment Dynamic assessment (nation specific)	L/F	Accuracy Time
Stage C				
Military training exercise		Mission specific military training exercises under a range of operationally relevant environments, tasks and group settings	F	Questionnaire RPE Mission evaluation by subject matter expert Pre-post objective measurements

[a] *Note:* AUS-LEAP = Australia load effects assessment program; GRF = kinetics—ground reaction forces; Insole = kinetics—insole forces; Exo = kinetics—exoskeleton forces.

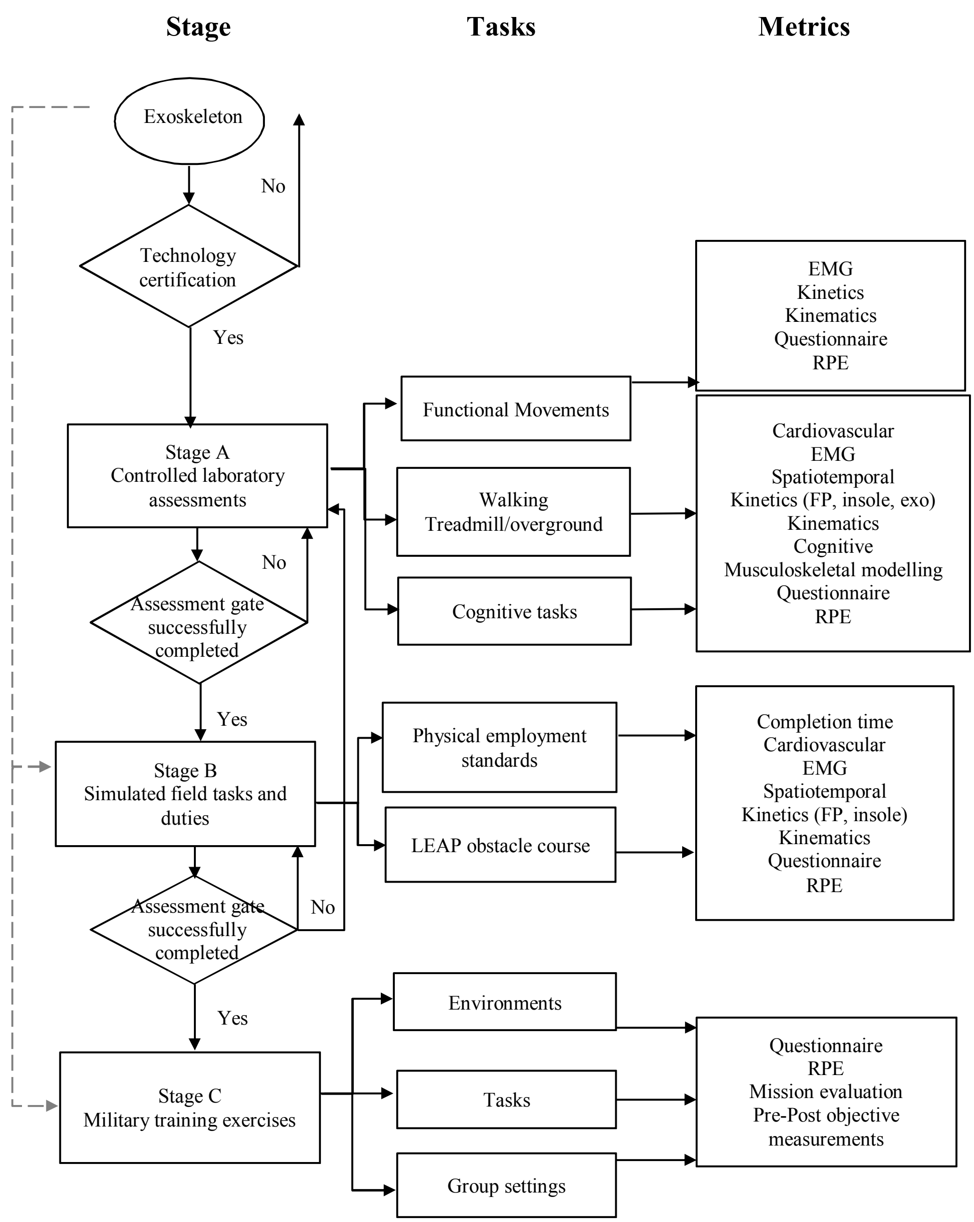

Fig. 2. Flowchart detailing the stage gated process from simple and controlled laboratory evaluations (Stage A) to more complex simulated and real-world military tasks (Stages B–C). Whilst a device is intended to progress from the top down, relevant components of the testing construct can be selected to best suit the intended application and maturity of the technology as detailed by the outer dotted grey line.

selection of relevant obstacles that are specific to the intended exoskeleton can be used (Table 1).

Lethality is one of the key NATO capability areas for the dismounted close combatant. While many current exoskeletons are not intended to directly affect marksmanship, it is important there are no negative impacts on shooting performances in a static or dynamic environment. Marksmanship tests are to be completed in accordance with the defined simulated and live fire weapon proficiency requirements set by the relevant Armed Forces.

Stage C involves the completion of mission specific military training exercises under a range of relevant environments (e.g. temperate, jungle, desert, arctic, urban, mountainous, etc.) (Table 1). At this stage, the exoskeleton under evaluation has likely reached a high level of technical readiness and should be tested under operationally relevant scenarios. Participants will be trained and experienced dismounted combatants with all tasks completed under the supervision of subject matter experts (i.e. Senior Non-commissioned Officer (NCO)) in order to ensure that they are completed in accordance with relevant tactics, techniques and procedures. Ideally, the same Senior NCO would observe the same mission profile completed under all three conditions (exoskeleton ON, exoskeleton OFF, and control).

The aim of Stage C is to evaluate the exoskeleton in a team environment and under real world settings to determine the potential utility within a military context and the impact on soldier mobility, sustainability, lethality, survivability and C4I. Multiple dismounted combatants and devices should be used with the focus on completing set mission profiles. Within this context, dismounted combatants should be afforded the flexibility to employ the exoskeleton in the manner that they believe best serves the mission. Data collected will be mostly subjective(Table 2) (questionnaires, including impact of the exoskeleton on individual users and the entire team) and ratings of perceived exertion (RPE) in addition to mission evaluations (i.e. rating of role and mission performance) from a subject matter expert. If possible, it is highly recommended that un-obtrusive field deployable assessment suits,

Table 2
A standard set of test metrics, measurement units and specific applications to collect objective and subjective data relevant to military exoskeletons.

Metric	Units	Application
Participant factors		
Demographic information		
Age and sex		
Handedness		
Rank, role, corp/trade, length of service and operational experience		
Strength and fitness		
Maximal aerobic capacity		
Leg power		
Unencumbered anthropometry		
Stature and body mass		
Segment lengths, breadths and circumference		
Skinfold thickness		
Physiology		
Cardiovascular function[10,38]		
Absolute oxygen consumption relative to BM or total mass (BM + exoskeleton)	$ml\ kg^{-1}\ min^{-1}$	L/F
Absolute heart rate	bpm	L/F
Net metabolic cost	$W\ kg^{-1}$	L/F
Surface EMG[39]		
Integral muscle activity	%	L/F
Muscle onset, offset and duration	ms	L/F
Thermal load[40,41]		
Surface temperature	°C	L/F
Core temperature	°C	L/F
Biomechanics		
Postural stability[11,42]		
Dynamic postural stability index	Unitless	L
Variability of GRF	CV/SD	L
Limits of stability	cm	L
COP length and excursion	cm	L/F
Spatiotemporal[43]		
Speed	$m\ s^{-1}$	L/F
Stride rate	Hz	L/F
Stride length	m	L/F
Duration of stance, loading, propulsion, single/double support and swing phases	s/%	L/F
Step width	m	L/F
Kinetics—ground reaction forces[43]		
Peak vertical and anterior/posterior GRF during the breaking and propulsion phases	N	L
Peak medio-lateral GRF during stance phase	N	L
Minimum vertical GRF during single-support phase	N	L
Loading and propulsion rates	$N\ s^{-1}$	L
Joint moments	N m	L
Kinetics—insole forces[43]		
Peak normal force during breaking and propulsion phases	N	L/F
Minimum normal force during single-support phase	N	L/F
Peak normal force at rearfoot, midfoot and forefoot during stance phase	N	L/F
Kinetics—exoskeleton forces[6,8]		
Force/torque applied/measured by the device during gait	N/N m	L
Kinematics[44,45]		
Peak joint angles (max and min)	°	L/F
Range of motion	°	L/F
Musculoskeletal modelling[19,46]		
Internal joint moments	N m	L
Muscle forces	$N\ kg^{-1}$	L
Cognitive[33,34]		
Response time	ms	L/F
Response accuracy	Correct/incorrect	L/F
Psychophysiology[37,47]		
RPE	15 point scale	L/F
VAS	0–100 VAS scale	L/F
Questionnaire (Supplementary files)	5 point Likert scale	L/F

Note: CV = coefficient of variation.

similar to that of Brandon et al.,[19] be used to collect physiological and biomechanical data throughout the mission, or before and after the completion of the mission. The combination of subjective and objective data in conjunction with mission evaluations will provide a comprehensive assessment of the effects of the exoskeleton(s) on mission performance.

When utilised as a staged process, relevant "reviews/gates" are to be conducted prior to progressing to the next stage and to assess the potential value proposition of the device (Fig. 2). Initially, a technology certification (safety assessment) of the device to be tested should be completed. The technology certification should ensure the safety aspects and hazards associated with use of the exoskeleton in relation to the activities to be performed have been considered and negated. Further, specific details such as the purpose of the device, specifications, materials, total mass, load ratings, previous test results and potential risks are determined and reviewed. A device should not progress to any human testing without first assessing quality and safety. Although it should be noted that due to the new nature of the technology there are no standard quality assessment tools or checklists for new exoskeletons to adhere to, therefore a thorough safety assessment by the chief investigator should be completed on every new device. However, there are currently a number of collaborative efforts around the world working on developing safety standards for exoskeletons (i.e. ASTM International, Committee F48 on Exoskeletons and Exosuits, National Institute of Standards and Technology (NIST) Exoskeleton Terminology Task Group, Wearable Robotics Association (WearRA) Standards Committee and International Organization for Standardization (ISO)/Technical Committee (TC) 299 Robotics).[16]

Following the completion of a testing stage, and prior to progressing to the next stage, it is necessary to complete a holistic assessment on the device's performance and safety (assessment gate). Any observed safety issues such as control system faults, device misalignments, durability concerns, thermal burden issues, significant restrictions in movement or general system failures should be addressed and rectified prior to advancing to the next stage. Additionally, any user subjective feedback about fit, comfort, or system performance should be important considerations before the system is permitted to advance. Following changes to a device, it should be considered if they were substantial and whether they necessitate previous stages/trials to be repeated to ensure a valid data set (Fig. 2).

3. Metrics

A standard set of metrics are presented for researchers and developers to select from dependent upon device specifications and the evaluation stage of interest . Objective measurements assess changes in the physiological, biomechanical, and cognitive characteristics of the user when wearing the exoskeleton. In addition, subjective measurements assess the psychophysiological effect in regards to their experiences with wearing and using the exoskeleton. Combining objective and subjective measurements throughout all stages of testing ensures a holistic assessment of exoskeleton performance. Objective measurements are separated into three main categories: physiological (cardiovascular and muscle function), biomechanical (spatiotemporal, kinetics and kinematics) and cognitive characteristics (response time and accuracy) of human performance. A range of key and commonly measured variables are presented, the majority of which can be measured reliably in the laboratory and the field.

Subjective measurement tools are presented to investigate the user's perception and views of wearing the device, including an example standardised questionnaire (Supplementary files), Borg 15-point RPE scale and a visual analogue scale (VAS).[37] A questionnaire was developed by the authors to assess the user's perspective on the fit and comfort, usability, integration and durability of the exoskeleton. Users should also be given the opportunity to provide any general comments on the device and highlight areas of discomfort or pain using a body-mapping tool.

4. Future directions

The development of a standardised evaluation framework for assessing the impact of an exoskeleton on the mobility of the dismounted close combatant was the primary focus of this paper. Nonetheless, as technology matures, improving exoskeleton design and assessment protocols to target the other four capability areas of the dismounted close combatant (lethality, survivability, sustainability and C4I) should be considered in future work. Further, developing a small number of simple and key metrics that combine objective and subjective measurements weighted to a specific task and device will significantly improve the evaluation and translation of findings to exoskeleton developers and military procurement specialists. Lastly, a critical area for future work will involve the further development of Stage C to improve the validly and reliability of evaluating exoskeletons during operationally relevant scenarios, whether it be at a team or individual level.

5. Conclusions

A structured and systematic methodology has been outlined, with the intent of enabling a more consistent and holistic assessment of exoskeleton performance across a variety of dismounted close combatant tasks, to obtain high quality quantitative and qualitative metrics related to device and personnel performance. The presented testing methodology is to be completed as a staged process, structured to progress from simple, controlled laboratory measurements to more complex field assessments. Representative tests at each stage of development that underlie the principles of each assessment stage are provided. Tests should reflect tasks and duties expected of the dismounted combatant, in addition to being suitable for each stage of the device's development cycle and maturity level (i.e. simple controlled tests first, followed by progressively more complex field tasks). Lastly, potential metrics and associated units that can be calculated during each test are presented to improve reporting and presentation consistency. These metrics entail a holistic approach, providing data on (1) the human response to wearing the exoskeleton (i.e. objective and subjective), and (2) the device's mechanical performance.

The development of a standardised methodology allows for the classification of exoskeletons in accordance with a common framework. Thus facilitating the potential to compare different devices and complete pre-/post-tests of a single device over time to assess design modifications or long-term effects of wear. These benefits will continue to ensure further advancement of the exoskeleton industry and support improved international collaboration. In doing so, this enables international military groups to better evaluate a system's potential, with the hope of accelerating the maturity and ultimately the fielding of devices to augment the dismounted close combatant and small team capability.

In summary, to evaluate an exoskeleton's performance within the military context we present a multi-disciplinary assessment utilising objective and subjective measurement techniques. We developed a three-staged testing procedure that progresses from simple controlled laboratory evaluations to complex in-field military specific exercises and simulated missions. Relevant components of the testing construct can be selected to best suit the intended application and maturity of the exoskeleton technology, thereby ensuring a robust and flexible approach.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jsams.2018.05.016.

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