Initial Evaluation of the Dermoskeleton Concept: Application of Biomechatronics and Artificial Intelligence to Address the Soldiers Overload Challenge

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ABSTRACT

A key challenge faced by military forces conducting dismounted operations is the excessive physical load burden resulting from the need to increase soldier survivability against asymmetric threats. The typical weight burden often exceeds 40 kg which is beyond the recommended maximum load limits which lead to acute and chronic musculoskeletal injuries. This paper presents the results of an experimental investigation of a new device called "Dermoskeleton" designed to counterpart the acute and chronic impacts of the distributed overload bearing of dismounted soldiers in all their tasks, e.g. marching and fighting modes. The performance of the initial prototypes was evaluated experimentally using standardized quantitative aerobic and anaerobic tests. The evaluation protocol included two conditions (with and without the device), with three weight criteria (no weight, 25 lbs, 50 lbs), and three (3) short/intense exercises tests: 1) performing the maximum amount of squats possible, 2) continuously climbing 3 flights of stairs for a period of 20 minutes and 3) conducting the Canadian Home Fitness Test (CHFT). The results showed a significant mechanical advantage (i.e. 48%) during the squat test. The current proof-of-concept prototype did not show a physiological benefit for stair climbing tasks but for one (1) participant. During the CHFT, the physiological effort with the device raised at about 5% to 10%. However, the participants perceived less physically exerting while loaded when using the dermoskeleton. The participants also noted that the system had considerable potential to enhance soldier mobility and reduce musculo-skeletal demands if key attributes of the system could be improved.

1.0 INTRODUCTION

1.1 The Challenge

A key challenge faced by military forces conducting dismounted operations is excessive physical load burden resulting from the need to increase soldier survivability against the asymmetric threats such as improvised explosive devices. The current load burden issue is becoming more critical nowadays with soldier modernization programs which focus on enhancing, at the soldier and section level, the Command, Control, Communication, Computing, Intelligence and Sensing (C4IS) capability and the related lethality mobility (i.e. navigation) aspects. The additional C4IS capability also creates a higher demand for power and energy making sustainability more difficult while amplifying the overload situation. In the current soldier system paradigm, any increase in survivability, lethality, and C4IS capabilities cannot be done without any penalty, i.e., the resulting physical overload will always compromise dismounted soldier mobility and physical performance, i.e., reducing traveling speed and distance, and the ability to overcome obstacles.

The typical weight burden of dismounted soldiers often exceeds 40 kg, i.e. more than 50% of the body weight, which is much beyond the recommended human factor safe load limits. This overload causes acute and chronic musculoskeletal injuries at the lower extremities joints and the back leading to related physiological and psychological health problems. These injuries often compromise the soldier's ability and readiness for his current and future missions. British soldiers were carrying more than twice the 80lb load carried by the Royal Marines and the Parachute Regiment in 1982 according to Giannengeli [7].

In the United States, the injuries linked to the stress of bearing heavy loads during repeated combat tours have increased the number of soldiers categorized as non-deployable as 257,000 acute orthopedic injuries have been reported in 2007 alone [24]. Musculoskeletal injuries are one of the main reasons US soldiers are unable to be deployed and the percentage which is presently at 14.5% could increase to 16% by 2012 reports Todd Lopez in Army News Services [23]. Soldiers unable to be deployed, leads to the need to add supplementary soldiers to fill these vacancies. Mr. Lopez notes that in 2009, 5000 additional soldiers were added and in 2010 another 10,000. Musculoskeletal injuries among Special Forces and Ranger units are equally alarming. Based on research conducted by James H. Lynch, MD, MS and Mark P. Pallis, Special Forces have the highest incidence of injury rate at 12.1 per 100 Soldier-months [14]. The highest percentage musculoskeletal conditions are in the back/neck (31%). The knees, ankles and shoulders follow at 10% each. These numbers highlight the potential burden there injuries can have on soldiers life, caregivers work load and military organizations' operations [14]. In summary, over the last decade, the musculo-skeletal injuries become a growing concern for military organizations and then has been started to be seriously studied by scientific community [13] [18]. Today, this specific medical issue is still in force and continues to be evaluated in order to find secure and efficient short and long term solutions; see References [1], [9], [11], [15], [2], [16] and [22].

For soldier modernization programs, balancing survivability, lethality, mobility, sustainability and C4IS is a complex system engineering challenge and often results in non ideal compromises. In addition to the incremental reduction of equipment weight through the use of lighter weight, multi-functions, and highly integrated materials and equipment systems, two emerging approaches have started to receive more attention to address the soldier burden challenge: offloading some of the charge to small unmanned ground vehicle (e.g. mule) [10] and the exoskeleton approach.

1.2 The Exoskeleton Approach

One way to address the overload issue of dismounted soldiers is the use of mechanisms named "Exoskeletons", in which the main function relates to the transfer of a portion of the body load carried by the user (weight and additional accessories), directly to the ground with an articulated mechanism running in parallel with the body structure. Because of their design, these devices are mainly dedicated to support a confined additional load such as carrying a rucksack (i.e. heavy load on the user's shoulder-back body structure) and to assist the human body in heavy-duty tasks such as such as lifting heavy loads repetitively. An exoskeleton supplies power at their respective joint mechanisms in order to support mechanically the additional load. Then, the articulated structure in motion transfers the said load directly to the ground with mechanical insoles. Therefore, the ground becomes an intrinsic element through the exoskeletons' design. In fact, the efficiency of exoskeletons to amplify the biomechanical body's strength is highly related to the capacity of the device to synchronize the work between the robotic structure and the ground.

The exoskeleton concept was created 60 years ago when the company General Electric crafted prototypes of autonomous manipulators and walking structures with the purposes of duplicating the biomechanical strength of the human body (www.cyberneticzoo.com). During the last 10 years, the field of human augmentation systems, or more precisely the exoskeletons, has been highly documented; see References [4], [5], [6], [17] and [19]. Nowadays, there are around ten (10) "modern" exoskeleton devices in development worldwide. For military applications, the two most known are the Human Universal Load Carrier (HULC) from Lockheed Martin (www.lockheedmartin.com), invented by Dr. H. Kazercooni at University of California at Berkeley (United States) [12], and the XOS System from Raytheon (www.raytheon.com).

The HULC is an untethered, battery powered, hydraulic-actuated exoskeleton designed to transfer the weight of localized heavy loads to the ground through the robotic legs while still maintaining movement with the user. The device, which weighs about 80 lbs, provides the capability to carry load up to 200 lbs at a speed up to 7 mph with sufficient battery energy for a 12.5 mile march. Laboratory testing on the HULC has looked at the metabolic cost of wearing the system [8]. During walking tests on treadmill, it was found that subjects significantly increased their mean oxygen uptake (VO_2) while wearing the device across 3 weight conditions and that they changed their gait characteristics by using shorter and faster strides with more knee flexion. The increase in mean oxygen uptake was attributed to the additional mass of the device [8]. Reductions in the maximal range of movement in the anterior-posterior and medial-lateral directions were also reported which could influence user's stability during movement [20].

The XOS system was originally developed by Sarcos and was labelled as the Wearable Energetically Autonomous Robot (WEAR). When Sarcos was acquired by Raytheon in 2007, the WEAR became the basis for the XOS 1 proof of concept exoskeleton. Further developments lead to the current version, the XOS 2, which uses hydraulic power. The device, which is tethered to an external power source, has a lifting ratio of 17:1 meaning that to lift 170 lbs the wearer only has to exert enough force to lift 10 lbs.

1.3 The Dermoskeleton Concept

Another human augmentation approach, based on the application of bio-mechatronics and artificial intelligence, was recently developed by the company B-TEMIA Inc. (www.b-temia.com) and which aims at addressing the distributed weight overload challenge. It is referred to as the "Dermoskeleton" concept. In this approach, the robotic mechanisms are designed to augment the biomechanical capability of the user while performing tasks that necessitate additional biomechanical energy in order 1) to execute properly the respective movements, 2) to restore, to maintain or to enhance the biomechanical capacity of the user with mobility dysfunctions, 3) to perform specific or repetitive tasks requiring strength and endurance, and 4) to protect the human body joint structure against acute and chronic injuries.

A dermoskeleton mechanism can be described as an automated orthopaedic supporting brace fully integrated onto a given joint-segments structure of a user's body without any interaction with the environment such as ground contacts using, for example, instrumented insoles. The device is designed so as to operate exclusively in cooperation with the associated body segments and is governed solely by the movements and the intentions of the user. Therefore, the additional biomechanical energy compensation performed by the dermoskeleton becomes totally independent of any interaction with the external environment.

A first step in the demonstration of the dermoskeleton concept was made with the development of the Knee Stress Release Device or K-SRD™ a motorized orthopaedic knee brace (Figure 1). This development is based on the knowledge and the expertise of the main author, Mr. Stéphane Bédard, in the field of biomechatronics. Mr. Bédard is also the inventor of the Power Knee, the first motorized leg prosthesis for above-the-knee amputees currently commercialized by Ossur hf and developed by Victhom Human Bionics Inc., a medical device company founded by Mr Bedard.

Specifically, the K-SRD™ is an autonomous motorized computer-controlled knee supporting device that actively assists the soldier's mobility during their various mobility tasks as well as to protect the user's lower extremities against acute and chronic injuries. The K-SRD™ is equipped with an advanced mechanism including sensors, an artificial intelligence (AI) module and a motor-damper system in order to manage the dynamic movements at brace joints. It eliminates musculoskeletal stress on the lower extremities (i.e. the lower back and the legs) by injecting biomechanical energy at the knee joint. Without any constraint in regards with the mobility spectrum, The K-SRD™ provides full movement assistance and increases the overall locomotion capability by artificially compensating around 50 kg of carried weight.

Figure 1 - Concept Design of the K-SRD™ from B-Temia Inc. (Photo courtesy of B-Temia Inc.)

The aim of this paper is to present the results of an experimental investigation of the operational proof-of-concept version of the Knee Stress Release Device (K-SRD™ version POC) as it applies to augmented mobility and reduced physiological workload. This investigation has been driven by the Defence Research Development Canada (DRDC) Toronto. An additional goal of this experimentation was to collect baseline data to provide a basis of comparison between the K-SRD™ version POC and any future evaluations of subsequent version of the K-SRD™ or any other exoskeletons.

2.0 METHOD

2.1 Introduction

For the experimental evaluation, recognized and standardized quantitative aerobic and anaerobic tests were used. The tests were executed using a controlled scientific methodology in a controlled environment with six (6) participants who had the opportunity to train with the device. The participants were highly active males between the ages of 20 – 29 (mean age=22.7 yrs.) who were recruited from the University of Guelph student community. The prototype used in the experimentation is shown in Figure 2.

Figure 2 - Device K-SRD™ used in the Experimentation (Photo courtesy of B-Temia Inc.)

The evaluation metrics were recorded in two conditions (with K-SRD™ version POC and without) and with three weight criteria (no weight, 25 lbs., 50 lbs.). Table 1 presents the test conditions for the experimentation. The protocol evaluated the acute performance of the K-SRD™ version POC through specific short/intense exercises. The experimentation did not evaluate the mid to long term benefits on the reduction on musculo-skeletal stress.

Table 1: Evaluation Protocol

Test Conditions	
No K-SRD version POC, No Weight	K-SRD version POC, No Weight
No K-SRD version POC, 25 lbs.	K-SRD version POC, 25 lbs.
No K-SRD version POC, 50 lbs.	K-SRD version POC, 50 lbs.

2.2 Tests

2.2.1 Total Number of Squats

Participants were instructed to perform the maximum amount of squats possible while wearing a 50-lb weighted vest with and without the K-SRD™ version POC system. Participants had to squat down (approximately 90º knee flexion) until their buttocks contacted a chair (height of 44.5 cm) at which they would then extend back up until their knees were fully extended. This counted as a single squat. Participants were given no timeline or cadence to which the squats had to be performed but simply to perform the maximum number they could without stopping.

2.2.2 Continuous Stair Climbing

Participants were instructed to continuously climb 3 flights of stairs for a period of 20 minutes while wearing a 50-lb weighted vest with and without the K-SRD™ version POC system. Participants had to walk at a cadence of 103 steps per minute for an estimated 2060 steps. Heart rate was measured before the start of the stair climbing activity and after each 2 minute interval.

2.2.3 Canadian Home Fitness Test

The Canadian Home Fitness Test (CHFT) is a validated measure of aerobic fitness in a general population [21]. This test used two normal 20.5 cm (8¾") steps and the CHFT long-playing audio recording. The recording played established cadences at which the participant stepped up and down to the rhythm. The participant stepped with a six pace cycle: two feet on the top step, one on the middle step, and both feet on the ground. Evaluation metrics for the CHFT included the heart rate (beats per minute). Given that there are 6 conditions (3 weight conditions by 2 K-SRD™ version POC conditions) each participant completed the CHFT 6 times. As such, sufficient time (minimum 20 minutes) between each iteration was provided such that there were minimal fatigue effects from the previous performance (i.e. heart rate returned to normal levels prior to the start of the next iteration). At the conclusion of each condition participants provided a rating of perceived exertion based on the BORG scale of rating of perceived exertion shown in Figure 3[2].

Exertion	RPE
no exertion at all	6
extremely light	7
	8
very light	9
	10
light	11
	12
somewhat hard	13
	14
hard (heavy)	15
	16
very hard	17
	18
extremely hard	19
maximal exertion	20

Figure 3 - BORG Scale of Perceived Exertion [2]

3.0 RESULTS

3.1 Squat Test

Maximum number of squats were performed while participants were wearing a 50-lb vest with and without the K-SRD™ version POC. Results are presented in Figure 4. As the squats were only performed once in each condition, there are no standard deviation error bars. Across all participants, more squats were completed with the K-SRD™ version POC than without it. The average number of squats completed with the K-SRD™ version POC (110) was statistically higher than without the K-SRD™ version POC (75) ($t(5) = -2.9$, $p < 0.05$). The maximum number of squats completed with the K-SRD™ version POC was 203; while the minimum number of squats completed without the K-SRD™ version POC was 50.

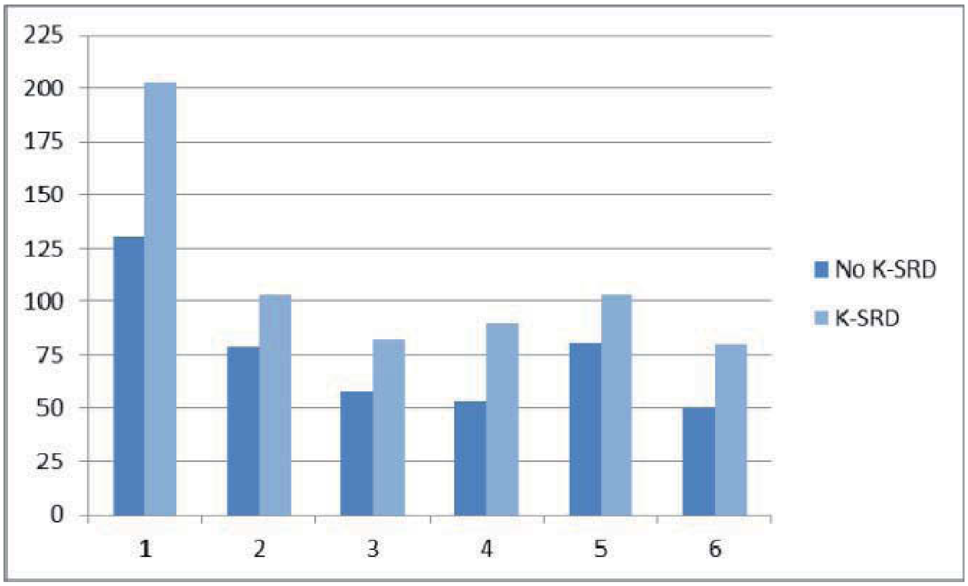

Figure 4 – Max Squats Completed with a 50-lb Vest with and without the K-SRD™ ver. POC

Mechanical advantage was calculated by dividing the difference in the number of squats performed by the number of squats performed without the K-SRD™ version POC using the following equation. Squats completed with mechanical advantage results are summarized in Table 2. Across participants, the mean mechanical advantage afforded by the K-SRD™ version POC for this task was calculated to be 47.5% ±17.2%.

$$MechanicalAdvantage = \frac{n_{squats_{KSRD}} - n_{squats_{NOKSRD}}}{n_{squats_{NOKSRD}}}$$

.

Table 2 - Summary of Squats Completed by Condition and Associated Mechanical Advantage

Participant #	Squats (n)		% Mech Adv.
	K-SRD	No K-SRD	
1	203	130	56.2
2	103	79	30.4
3	82	58	41.4
4	90	53	69.8
5	103	81	27.2
6	80	50	60.0

3.2 Continuous Stair Climbing Test

Twenty minutes of continuous stair climbing while wearing a 50-lb vest in both trial conditions (with and without the K-SRD^{TM} version POC) presented varied results. Heart rate was recorded in 2-minute intervals starting from rest. Without performing a higher order curve fitting analysis or an integration of the HR-Time curves, it is difficult to accurately interpret the amount of physiologic work required by the participants to complete the task in each test condition. Superficially, it can be observed that, over the course of the 20 min task, four (4) participants maintained heart rates that were more elevated with the K-SRD^{TM} version POC than without it (participants 1, 3, 4, and 5). This suggests that these participants generally required more physiologic effort to complete the task with the K-SRD^{TM} version POC than without it. However, Participants 6 did show a reduction of his heart rate over the period; suggesting less physiological effort while wearing the device. Participant 2 showed mitigated results where the impact of wearing the device toggled between a positive and a negative effect on the heart rate.

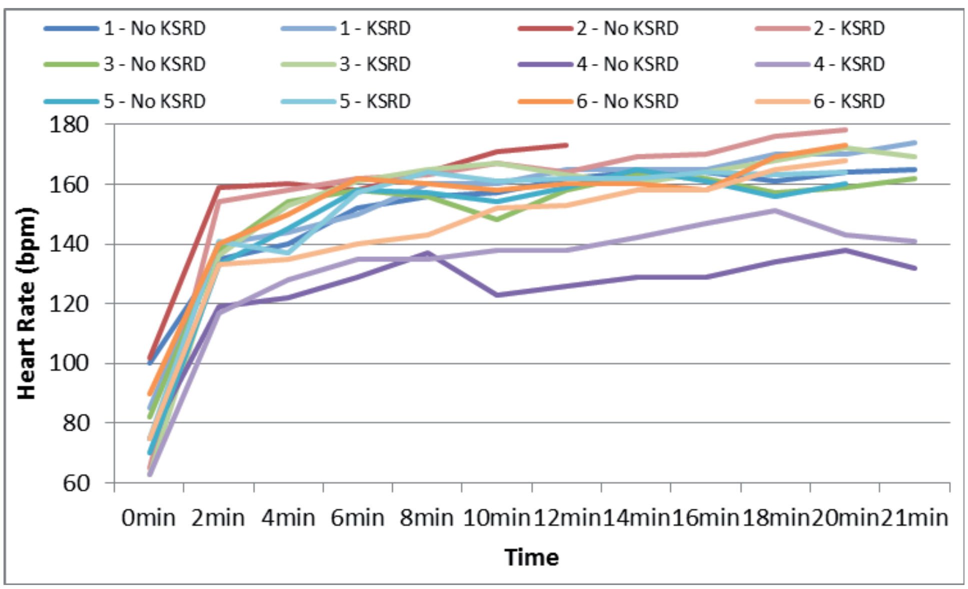

Figure 5 - Participants' Heart Rate for 20 Minutes of Continuous Stair Climbing with 50 lbs

3.3 Canadian Home Fitness Test

Results indicated that after each 3 minute CHFT exercise, heart rate progressively increased across all three weight conditions, across both K-SRD™ version POC conditions. These results are summarized in Figure 6. A multivariate analysis of variance was performed on the within-subjects effects of the K-SRD™ version POC, weight, and time on heart rate; heart rate was significantly affected with each of these main effects. There were significant main effects of K-SRD™ version POC, load, and time on heart rate ($p < 0.01$). Heart rate did not reveal significant K-SRD™ version POC by load interactions ($F(2)=1.46$, $p= 0.2779$). For the main effect of the K-SRD™ version POC condition, heart rate increased significantly with the addition of the K-SRD™ version POC ($F(1)=23.45$, $p=0.0047$).

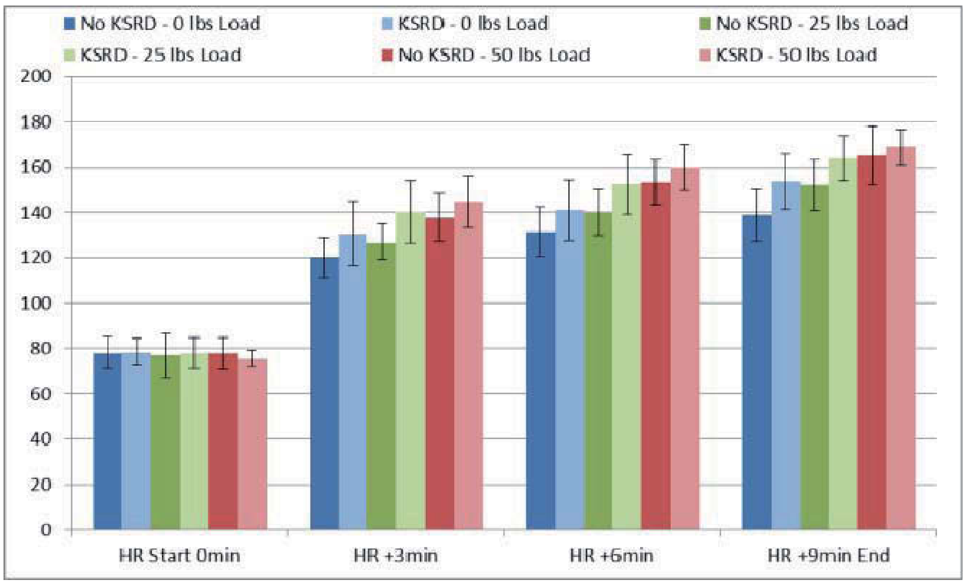

Figure 6 - CHFT Heart Rate Results by Condition

In addition to heart rate, participants recorded their rating of perceived exertion (RPE) at the conclusion of each CHFT task according to the BORG scale. Generally, as load increased, participants' rating of their perceived exertion increased accordingly. For the no-load test condition, the mean RPE without the K-SRD™ version POC was 8.5 and was 9.7 with the K-SRD™ version POC; this represents a significant difference of 1.2 ($t(5) = -2.9$, $p=0.034$). With respect to the 25-lb load, participants rated their mean perceived effort without the K-SRD™ version POC at 11.7 and 11.8 with the device; this difference was not significant ($p=0.822$). At the 50-lb load, participants rated their mean perceived effort of performing the CHFT task with the K-SRD™ version POC as being less laborious than when performing it without the device (14.2 without the K-SRD™ version POC versus 13.7 with the device); this result was not significant ($p=0.624$). These results are presented in Figure 7.

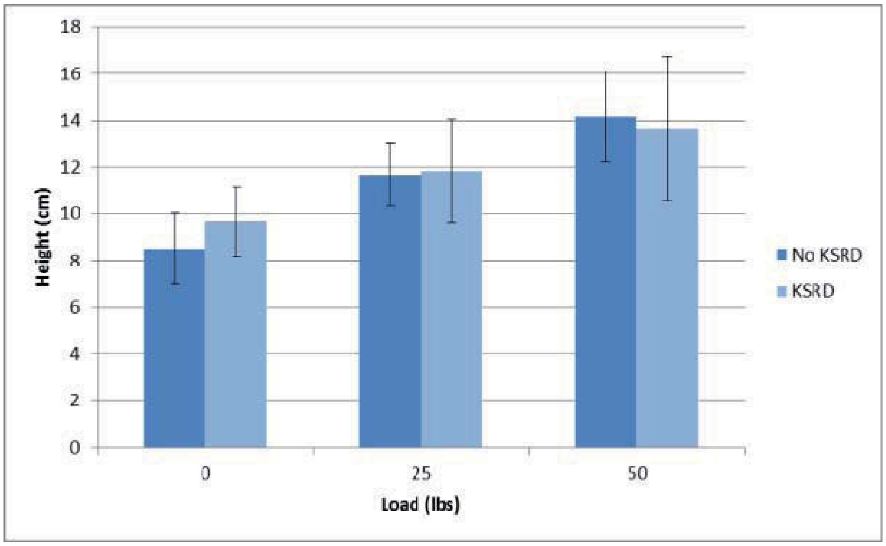

Figure 7 - BORG Rating of Perceived Exertion for the CHFT Task by Condition

4.0 DISCUSSION

The K-SRD™ version POC system aids in knee extension at cyclic rates below 5 mph. One of the tasks that isolated this movement was that of the squat. Due to the mechanics of the steady, continuous squat, this task was not affected by the weight or the distal placement, the speed limitations, nor the mechanical resistance of the K-SRD™ version POC, or by the movement complexities of the task. In this instance the K-SRD™ version POC provided a substantial benefit to the user. As previously mentioned, there was a 47.5% mean mechanical advantage when using the K-SRD™ version POC. This suggests that in its simplest form the K-SRD™ version POC does in fact provide a benefit to the end user in allowing them to achieve greater amount of squats or conversely the same number of squats with less effort.

We would assume that during a more strenuous stair climbing task, as compared to the CHFT, that the benefits of the K-SRD™ version POC would become more evident. This was not the case in the continuous stair climbing task. This test cannot be viewed as a longer version of the CHFT. In the CHFT participants ascended two steps and then descended the same two steps backwards for one cycle. In the continuous stair climbing task participants climbed consecutively 3 flights of stairs and then turned around and walked down the 3 flights of stairs facing forward. For four (4) participants, the heart rate versus time curves indicate that there does not appear to be a benefit with the K-SRD™ version POC during the 20 minutes of continuous stair climbing. This may be due to the extra physiological cost of carrying and moving the KRSD version POC down the stairs when there is no mechanical benefit imparted by the system. However, Participants 6 did show a physiological benefit with the device whereas the results of the Participant 1 are inconclusive.

One expectation of the K-SRD™ version POC system was that it would provide benefits to the user over extended periods of walking or while carrying heavy loads. Rating of perceived exertion from the CHFT partially supported this expectation. Initially, when there was no load participants rated the "with K-SRD™ version POC" condition as being more physically exerting. When the 25-lb load was added the gap between the ratings of perceived exertion became narrower. Finally, when the participants wore the 50-lb vest participants rated the "with K-SRD™ version POC" condition as less physically exerting than the "without K-SRD™ version POC" condition. This suggests that there is a perceived benefit of the K-SRD™ version POC when more weight is added. This also suggests that there is a perceived "cost" of exertion to wearing and carrying the K-SRD^{TM} version POC alone. Anecdotally, participants noted that they did not feel they worked as hard when wearing the K-SRD^{TM} version POC during the loaded conditions. However, based on our heart rate measured, there was no significant reduction in physiological effort with the K-SRD^{TM} version POC. There is a possibility that, during the loaded conditions, participants changed their motor control patterns so that they relied more on the K-SRD^{TM} version POC and thus decreased the level of perceived exertion. However, changing the motor control pattern would increase the metabolic cost, and potentially heart rate, thereby masking any benefit of the K-SRD^{TM} version POC for physiological effort.

5.0 CONCLUSION

Results from the experimental evaluation of the K-SRD^{TM} version POC showed that a significant mechanical advantage (i.e. 48%) is provided during the squat test. Further development of the K-SRD^{TM} will be focusing on transferring this mechanical benefit to more locomotion tasks. The current prototype (K-SRD^{TM} version POC) did not provide a physiological benefit for stair climbing tasks but for one (1) participant. During the Canadian Home Fitness test (CHFT), the physiological effort with the device raised at about 5% to 10%. However, the participants perceived the use of the K-SRD^{TM} version POC less physically exerting while loaded. Despite the limited measurable performance benefits of the current K-SRD^{TM} version POC, participants noted that the concept has many positive attributes for an initial prototype and that the system had considerable potential to enhance soldier mobility and reduce musculo-skeletal demands on the soldier if key attributes of the system could be improved.

The demoskeleton concept is a novel emerging solution applying biomechatronics and artificial intelligence technologies designed to address the current dismounted soldiers distributed weight overload challenge. The concept has also the potential to change the soldier systems design paradigm, as it will allow for optimising both survivability and mobility, i.e. not one to the expense of the other. This will contribute to increase the operational effectiveness and figthability of dismounted soldiers in the complex battle space of the future. The dermoskeleton is a concept which has the potential to become truly disruptive and lead to important capability overmatch.

6.0 ACKNOWLEDGEMENTS

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