BEN-GURION UNIVERSITY OF THE NEGEV
FACULTY OF ENGINEERING SCIENCES
DEPARTMENT OF INDUSTRIAL ENGINEERING AND MANAGEMENT

EVALUATION OF A PASSIVE KNEE EXOSKELETON FOR VERTICAL JUMPING

THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE M.Sc. DEGREE

By: Coral Ben David

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Supervised by: Dr. Raziel Riemer

Author: ……coral……………….. Date: 24/01/2021…….

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Chairman of Graduate Studies Committee: ……………. Date: 25/1/2021..

November 2020

Abstract

In recent studies exoskeletons have been proven to augment human mobility and facilitate daily tasks such as walking, running, and hopping. Most exoskeletons are designed to reduce the effort (i.e., metabolic rate) expended by their user while performing aerobic tasks. However, exoskeletons that assist fast, explosive movement, specifically vertical jumping, have yet to be thoroughly examined. Furthermore, a fundamental lack of understanding still prevails regarding the interactions between humans and exoskeletons.

Our main hypothesis was that a passive exoskeleton has the ability to increase vertical jumping height without providing additional external energy. The designed passive knee exoskeleton consists of springs which act in parallel to the quadriceps femoris muscle. These springs store energy in the negative-work phase, during knee flexion, and inject the energy in the consequent positive-work phase, during knee extension. The stored energy can then be utilized to increase the jumping height.

The exoskeleton was tested on ten healthy participants, in two separate experimental sessions, in which they aimed to jump as high as possible. In the first session, participants jumped under five conditions- two without the exoskeleton and three with the exoskeleton and three different spring stiffness levels. The participants jumped without receiving instructions on how to use the exoskeleton. Results showed an increment in jump height as spring stiffness increased, and no difference in height between the jumps with and without the exoskeleton. In the second session, participants jumped under two conditions- without the exoskeleton and with the exoskeleton with the highest spring stiffness level. The participants were trained to better utilize the exoskeleton by exploring different jumping techniques in order to improve their adaption to the exoskeleton.

The second session, including instructions and training with the exoskeleton, resulted in a 6.4%±0.9% (mean ± SE) increase in jumping height compared to jumping without the exoskeleton. To the best of our knowledge, this is the first time a passive exoskeleton is shown to be successful in augmenting vertical jumping. The knowledge accumulated during this study regarding the human-exoskeleton interaction has the potential to assist in the development of fast explosive motion exoskeletons.

Subsequently, these results will be used in our laboratory for the development of a model for the human-exoskeleton interaction using an optimal control process, that aims to enable developing different types of exoskeletons in a faster and more economical way.

Sections of this work were presented in the 2019 International and American Society of Biomechanics conference in Calgary, Canada. This work was also presented in 2020 The International Symposium on Wearable Robotics conference in Vigo, Spain (Virtually). Additionally, we are also in preparations for a publication in Science Robotics.

Key words: Adaptation, Augmentation, Passive Exoskeleton, Vertical Jumping

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I would also like to thank Professor Yisrael Parmet for his advice regarding the proper statistical methods. I extend my thanks to Benyamin Shargorodski for assistance in conducting the experiments, and Shimon Richter and Aviel Maman for their contribution to the development of the force-measurement system and the model meant to predict the spring forces.

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1. Introduction

1.1 Exoskeletons

The field of wearable exoskeletons has developed tremendously over the past decades. Exoskeletons are primarily designed for rehabilitation or augmentation of normal physical human performance. Enhancing the physical performance of humans in different activities could improve user efficiency and would be extremely useful for workers in a physically demanding environment, such as industrial workers, police officers, soldiers, and firefighters.

1.1.1 Methods and parameters for exoskeletons' evaluation

When designing and developing an exoskeleton, it is essential to determine its purpose and the manner in which it should assist the user. In order to meet the design goals, one must examine the parameters that indicate the degree of success, how it is operated, and its structure.

One of these parameters is the Electromyography (EMG) signal, a biomedical signal that measures the electric potential generated by muscle cells during their activation. A larger signal means greater muscle force production. The EMG signal can be obtained using invasive electrodes (needles) or by non-invasive electrodes, also known as surface EMG (sEMG), placed on the surface of the skin. Analyzing EMG signals requires noise filtering to obtain the most accurate signal (Reaz, Hussain, & Mohd-Yasin, 2006). To process the EMG signal, several steps need to be performed: (1) Raw signal amplification, (2) Analog filtering, (3) Analog to digital conversion and digital high-pass filtering, (4) filtering by one of two methods (4.a) "linear envelope" that rectifies and uses digital low pass filter, or (4.b) computing the Root Mean Square (RMS) value of the signal within a window which "slides across" the signal, and lastly (5) determines the times in which muscles "turn on" and "turn off" (Rose, 2014).

The second group of parameters is the kinematics (i.e., motion) and kinetics (i.e., forces and torques) parameters, examining the exoskeleton's impact on user movements. Using an exoskeleton will, in most cases, lead to a change in the movement of the human body. This change can be measured by examining various kinetics and kinematics indices such as the center of mass, the joints' angles, forces, and moments. Motion capture systems are used for recording and processing the human movement, and force plates are used for measuring the external forces. Signal processing filters need to be implemented in order to remove unwanted components from a transmitted signal. Most often, this means removing some frequencies to suppress interfering signals and reduce background noise. The most common filter used in the motion field is Butterworth, which is designed to have as flat of a frequency response as possible. In addition, since there could be measurement errors and soft tissue artifacts, it is recommended to use another noise reduction method. There are two common methods: (1) 6DOF that performs segment optimization by assuming a rigid segment, and treating each segment individually. (2) Inverse Kinematics (IK) for global optimization by computing a "best match" between the actual markers and the model determined markers, therefore it allows errors in the actual marker locations (Kainz et al., 2016; Mentiplay & Clark, 2018). After using one of the methods for soft tissue artifact reduction, the forces and moments in the joints can be obtained by using the Inverse Dynamics method (Winter, Patla, Frank, & Walt, 1990), which uses kinematic measures, the anatomical structure of the subject (e.g., height and weight), and combines them with measured external forces to estimate the joint forces and moments.

Finally, metabolic rate is the primary measure for exoskeleton success in aerobic activities such as walking and running. It is the amount of energy the organism needs per unit of time (Maxwell Donelan, Kram, & Arthur D., 2001). This measure is calculated by the percentage of oxygen consumed and the percentage of carbon dioxide emitted from the body using indirect calorimetry systems. Over the past decade, several studies have shown that metabolic power can be reduced using an exoskeleton during walking (Collins, Bruce Wiggin, & Sawicki, 2015; H. J. Lee et al., 2017; Lim et al., 2019; Malcolm, Derave, Galle, & De Clercq, 2013; Mooney & Herr, 2016) and running (G. Lee et al., 2017; Nasiri, Ahmadi, &

Ahmadabadi, 2018; Simpson et al., 2019). One study even examined an exoskeleton that assists both walking and running (J. Kim et al., 2019). Metabolic rate examination is used only when the body is engaged in aerobic activity but could not be used to evaluate exoskeletons assisting anaerobic and explosive power activities.

1.1.2 Classification of exoskeletons

Sawicki *et al*. (2020) reviewed peer-reviewed publications that report on exoskeletons that improve user walking or running efficiency, and categorized these as either “tethered” or “autonomous.” Furthermore, they classified autonomous systems as active or passive. Active exoskeletons contain actuators that add energy to the motion (J. Kim et al., 2019; S. Lee et al., 2018), whereas passive exoskeletons use passive elements such as springs and dampers (Nasiri et al., 2018; Simpson et al., 2019; Walsh, Edo, & Herr, 2007). Nuckols *et al*. (2020) describe the concept of energy transfer from one phase of motion to the next, either within or across joints. This concept can be used to design passive exoskeletons that extract energy during the negative phase and inject the energy in a later positive phase. Passive exoskeletons are typically cheaper and lighter than active exoskeletons, whereas active exoskeletons are more adaptable given their ability to exploit any torque-time profile.

An alternative way to classify exoskeletons is by the number of joints they assist. Exoskeletons for lower-limbs can either assist only one joint (i.e., hip, knee, or ankle) or assist two or more joints by span cable or spring through all these joints. Based on the Sawicki *et al*. (2020) review, most of the lower-limb exoskeletons who succeeded in augmenting walking or running were one joint exoskeletons (e.g., Collins, Bruce Wiggin, & Sawicki, 2015; Lim et al., 2019; Nasiri, Ahmadi, & Ahmadabadi, 2018), while only one multi-joint exoskeleton augmented walking with load-carriage while assisting both the ankle and hip joints. This is most probably due to the complexity of building and controlling multi-joint exoskeletons.

1.1.3 The design process of an exoskeleton

Despite the significant amount of work that has been devoted to the design and control of exoskeletons, there is still much to be done. In particular, a lack of knowledge about human-exoskeletons interaction remains, which is critical to exoskeletons' successful design.

In such devices' design, several interconnected parameters must be taken into consideration (e.g., actuator type, gear ratio). Since the components influence one another, the design procedure is a complicated task. Today, the primary method for exoskeleton design is building and rebuilding several prototypes until the desired parameter values are reached (Guizzo & Goldstein, 2005), making it both costly and time-consuming. A recent exciting development is a design method in which researchers adjust exoskeleton parameters and test their effect on human performance online. Examples include adjusting torque profiles for the ankle (Zhang et al., 2017) or the hip during walking with a soft exosuit (Ding, Kim, Kuindersma, & Walsh, 2018). However, even with this approach, there is still a need for multiple experiments and the use of complex, expensive devices. A suitable solution to the above problems in exoskeleton design may lie in optimization-based motion prediction. This methodology assumes that human motions aim to optimize some performance measures, such as jerk (i.e., the rate of change of acceleration) (Flash & Hogan, 1985) and energy expenditure (J. H. Kim, Malek, Yang, & Marler, 2006). In this methodology, human motion is determined by solving an optimization problem with constraints, such as maximum joint torque or maximum joint angle. Designs of exoskeletons with simulation were reported by several studies that have focused on the influence of the exoskeleton on human movement during continuous and non-continues tasks (Farris, Hicks, Delp, & Sawicki, 2014; Jackson, Dembia, Delp, & Collins, 2017; Millard, Sreenivasa, & Mombaur, 2017; Ong, Hicks, & Delp, 2016). However, most of the simulations developed were not verified by an examination of a similar exoskeleton in experiments. Hence, while the objective function might be improved in the simulation, it might not function in reality.

1.1.4 Exoskeletons' adaptation

As mentioned earlier, exoskeletons can alter the human body's natural movement and make it more efficient at locomotion. However, the human body needs to adapt to these changes in a process called motor adaptation. Humans regularly modulate muscle activity during movement in response to environmental (e.g., terrain, obstacles) and neuromuscular factors (e.g., fatigue, muscle strength). Since the exoskeleton causing neuromuscular perturbations, the human body needs to adapt to it (Gordon & Ferris, 2007). Robertson, Farris, and Sawicki (2014) showed that adaptation to an exoskeleton for hopping would reduce muscle activation while increasing the spring stiffness. Sawicki and Ferris (2008) found reductions of metabolic rate up to 13% during walking, while using a powered exoskeleton compared to unpowered, but only after an adaptation period of up to 90 min. Since then, several studies have shown an adaptation to the exoskeleton after ~20 min of walking (Collins et al., 2015; Galle, Malcolm, Derave, & De Clercq, 2013).

Selinger *et al*. (2015) studied humans walking with novel exoskeletons and found that in order to find the optimal step frequency, which minimized their metabolic rate, subjects had to carry out an exploratory session in which they walked at fast and slow step frequencies. Hence, the subjects had to perform motor adaption in each walking speed they explored.

Therefore, an examination of motor adaptation is crucial in understanding the interaction between the human and the exoskeleton and could contribute to more efficient utilization of the exoskeleton.

1.2 Vertical Jumping

Vertical jumping starts with a negative-work phase during hip and knee flexion and ankle dorsiflexion. In this phase, the jumper lowers their body into a squat position. The next phase is a positive-work phase that includes hip and knee extension and ankle planter-flexion. This phase extends from the start of upward movement until the toes leave the ground (Fukashiro

& Komi, 1987). In addition, hip and knee joint moments have been reported to exceed ankle moments during a vertical jump (Bobbert & van Ingen Schenau, 1988; Fukashiro & Komi, 1987; Vanezis & Lees, 2005).

There are two primary vertical jumping techniques. The first is the countermovement jump, where the jumper starts from an erect position and makes a downward movement before starting to push-off. The second is squat jump, where the jumper is instructed to start from a semi-squatted position and make no countermovement (Bobbert, Gerritsen, Litjens, & Van Soest, 1996; Van Hooren & Zolotarjova, 2017).

1.3 Exoskeleton for vertical jumping

The use of an exoskeleton to augment walking, running, and leaping was already proposed in 1890 by Yagn (1890), who presented a theoretical design consisting of long bow springs operating parallel to the legs. Later, Grabowski and Herr (2009) designed a full-leg exoskeleton that reduces the metabolic cost during hopping by up to 30% from 2.0 to 2.6 Hz. Farris and Sawicki (2012) also designed an exoskeleton that reduces the metabolic cost during hopping. Their design includes a passive spring-loaded ankle exoskeleton that reduces the metabolic cost of hopping by 12% at 2.5 Hz.

However, hopping is an aerobic activity and differs from fast, explosive movement, such as vertical jumping. To the best of our knowledge, only Kim *et al*. (2015) have heretofore attempted to build and test an exoskeleton for fast, explosive motion. Their passive-elastic ankle exoskeleton uses a one-way clutch mechanism to enhance vertical jumping. In the pilot tests, the subjects nearly reached their maximum vertical jump height with the exoskeleton, but could not surpass it.

In this study, we built and tested experimentally a passive knee exoskeleton with springs acting parallel to the muscle. The springs store energy during the negative-work phase and return the energy in the following positive-work phase. We focused on the knee joint because of the large moments involved with this joint and because the design is simpler than for the hip joint.

There are two main goals for this study. The first goal is to test whether a passive exoskeleton can improve vertical jumping height. The second goal is to learn about the human-exoskeleton interaction and to validate a simulation of jumping with an exoskeleton. This simulation will later be used for developing different types of exoskeletons in a faster and more economical way.

2. Method

2.1 Participants

Ten healthy males (age 24.9 ± 2.7 years; mass 73.0 ± 3.7 kg; height 1.74 ± 0.03 m) participated in the study. Note that only a single exoskeleton was available, so only subjects who fit the exoskeleton were selected. Two additional subjects dropped out during the experiments, one of whom was afraid of using the exoskeleton and thus did not bend his knees during the jump. For the other subject, the exoskeleton proved too narrow at the knee, causing pain during the jump. All subjects provided written informed consent before participation in the study (see appendixes 6.4-6.7). The study was approved by Ben-Gurion University's Human Research Institutional Review Board.

2.2 The Designed Exoskeleton

For this study, we designed and constructed the passive knee exoskeleton shown in Fig. 1. The exoskeleton consists of aluminum 6061 frames, attached to the leg with the help of wide Velcro® straps. Rubber springs (typically used for spear guns) to contribute to moment are located near the knee and are aligned parallel to the quadriceps femoris muscle. The total mass of the exoskeleton is about 1.5 kg per leg. Specifications of the exoskeleton components are found in Table 1.

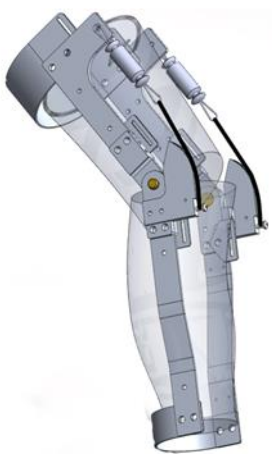


Figure 1. The designed knee exoskeleton

Table 1

Contributions to Passive Exoskeleton Mass by Component

Segment	Mass
Aluminum frame	**1272 g**
Net spring	14.8 g
Spring with attachments	24.4 g
Three springs for highest stiffness	**73.2 g**
Velcro stripes with attachments	**160 g**
Total mass	**1505.2 g**

This table gives the total mass for an exoskeleton with the highest spring stiffness, for one leg.

2.3 Protocol

Two experimental sessions were performed. In the first session, the subjects jumped as high as possible without the benefit of instructions on how to utilize the exoskeleton for jumping. In the second session, the subjects were first trained on how to utilize the exoskeleton before performing their jump attempts. The two sessions were performed as in previous studies of walking with exoskeleton (Collins et al., 2015; Galle et al., 2013), showed that the subjects adapted to the exoskeleton and that their performance improved from one session to the other.

2.3.1 The first session protocol

In the first session, the subjects jumped vertically under five conditions: without the exoskeleton (NoExo); with the exoskeleton but with no spring connected (Exo0) (in this case, the exoskeleton is a deadweight); with the exoskeleton and four springs that provided in total 70 N m at a 90° knee bend (Exo1); with the exoskeleton and six springs that provided in total 105 N m at a 90° knee bend (Exo2); and again without the exoskeleton (NoExo2). The exoskeleton tests were conducted in random order, and tests NoExo at the beginning and NoExo2 at the end served as control conditions. Before performing each condition with the exoskeleton, the subjects free jumped with it for five minutes to adapt to it. The subjects then jumped vertically eight times under each condition, and the data were collected from the last five jumps each time.

The moment values provided by the exoskeleton are based on tensile tests of the rubber springs that relate spring force to strain ratio. The tests were conducted with the help of a universal testing machine (Hounsfield, H10KT). The 70 and 105 N m moments are equivalent to a spring stiffness of 38 and 57 N m/rad, respectively, which reflect a compromise between keeping the device compact and lightweight using relatively affordable components and providing larger moments. Furthermore, based on previous studies (Bobbert & van Ingen Schenau, 1988; Fukashiro & Komi, 1987; Vanezis & Lees, 2005) with professional athletes, these values provide about 20% and 33% peak knee moment during the jump, respectively.

2.3.1 The second session protocol

Due to COVID-19 restrictions, the second session was conducted about three months after the first session. Since the results from the first session reveal a positive correlation between spring stiffness and jump height, the second session included two conditions only: one without the exoskeleton (NoExoS2); and one after training with the exoskeleton with springs that provided 105 N m at a 90° knee bend (Exo2S2).

To improve the adaption to the exoskeleton in this session, we had the subjects explore different jumping techniques. The experimental protocol was adapted from Gast (2019), who found that walking on rough terrain while exploring various walking speeds reduces the time for convergence to minimum cost of transport during walking at preferred speed. In addition, in a study of human walking with exoskeletons, Selinger (2015), found that subjects discovered their optimal step frequency in exploratory sessions in which they walked at high and low step frequencies. Thus, after jumping without the exoskeleton, the subjects in the present work were trained to better utilize the exoskeleton. The training consisted of executing four squat jumps from different starting postures, where the main change was the depth of the squat. We also gave minimal instructions regarding possible ways to achieve this posture (e.g., maximum bend at the knee, flat feet, and straight back). We then chose the jump with the maximum vertical height and tweaked the technique to optimize the results. Since we noticed that the subjects increased the distance between the feet when using the exoskeleton during the first session, in this session, they were instructed to keep their feet at pelvic-width, to the extent possible. Feet at pelvic-width will cause the forces to be on a more vertical axis and potentially contribute to the jump height. Each subject executed up to ten training jumps to adapt to the new jumping technique with the exoskeleton. A schema of both experimental protocols is presented in Fig. 2.

In both sessions, the subjects followed a given warm-up routine of walking on a treadmill at 1.6 m s^{-1} for four minutes, followed by free jumping. Then, for each jump, they were instructed to jump as high as possible with their hands crossed on their chest (see Fig. 3). To prevent fatigue, the subjects rested for two minutes between jumps. Fig. 3 shows the phases of the jump.

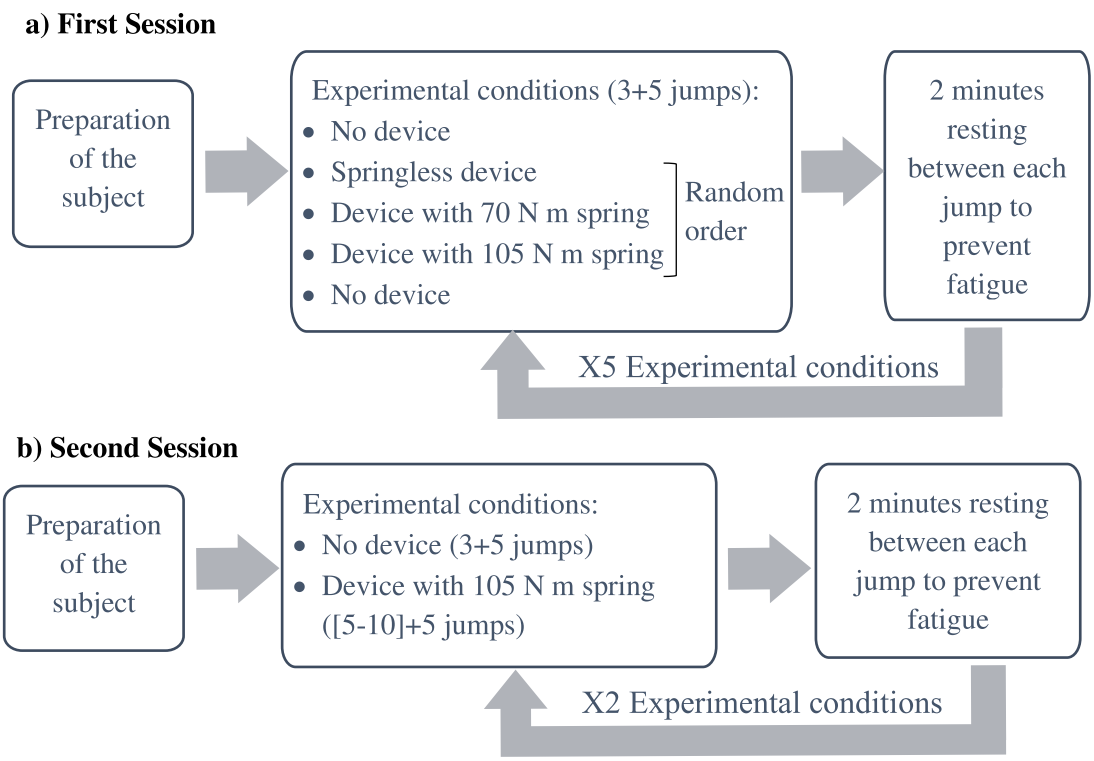


Figure 2. The experimental protocol of the two sessions

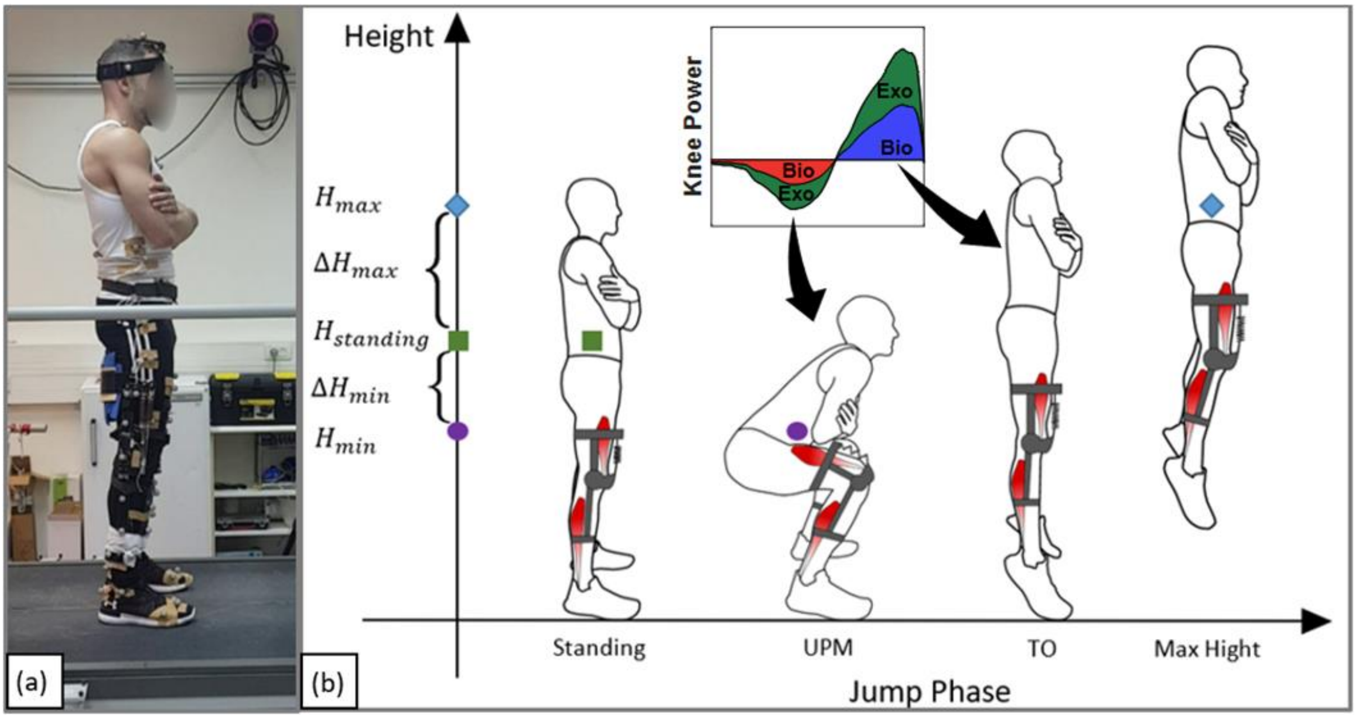


Figure 3. The jumping experiments. a) The subject wearing the exoskeleton and preparing for vertical jumping under the experimental protocol. The subject is standing on an instrumented treadmill while markers and EMG sensors are attached to him. b) The different phases of the vertical jump: Standing, the starting position for the Upward Movement (UPM), Take-Off (TO), and reaching Max Height. During knee flexion, the springs are stretched, and from UPM to TO, the stored energy in the springs is added to the biological energy. The COM height parameters are also presented according to the phase of the jump. The muscles in red represent the knee extensor muscles and ankle plantar flexors. We measured EMG from Rectus Femoris and Gastrocnemius.

2.4 Data Collection

The motion of the subjects was recorded using fourteen cameras operating at 179 Hz (Qualisys, Gothenburg, Sweden) and that tracked reflective markers fixed to the subjects and to the exoskeleton. The reflective marker set can be found in Appendix 6.1. Ground reaction forces were recorded at 2040 Hz by using an instrumented treadmill (Bertec, Columbus, OH, USA). During one jump, the force plate initialization malfunctioned, so this jump was omitted. The activity of the right-leg rectus femoris and gastrocnemius muscles was measured by using surface electromyography (sEMG) sensors (Trigno Wireless System, Delsys, Boston, MA, USA) at 2000 Hz. We chose to examine these muscles because of their contribution to vertical jumping (Goodwin et al., 1999; Pereira, Machado, Miragaya, Pereira, & Sampaio-jorge, 2008; Sotiropoulos et al., 2010; Tsai, Liu, Chen, & Huang, 2004). The skin around the attachment of the EMG sensors was shaved and scrubbed clean with 70% alcohol. The EMG sensors were attached to the body by adhesive tape provided by the manufacturer. Yet, due to sweating and shock during landings, the EMG sensor on the rectus femoris muscle moved for three subjects during the final tests. Additionally, during the final tests, the EMG sensor on the gastrocnemius muscle also moved for two subjects. Thus, the data from these jumps were not used.

2.5 Data Analysis

The data from all three systems were recorded and synchronized using Qualisys Track Manager software (Qualisys, Gothenburg, Sweden). In this software, I built an Automatic Marker Identification (AIM) model that automatically labels the markers (see Appendix 6.2). Then, the data were exported into Visual 3D (C-Motion Inc., Rockville, MD, USA), which uses bottom-up inverse dynamics (Winter, 2009) with six degrees of freedom to calculate joint angles, angular velocities, body center of mass (COM), moments, and powers (see Appendix 6.3). The angles for the ankle, knee, and hip joints are defined as follows: the ankle angle is measured from the foot to the shank; when standing, it is about 90° and increases during plantar flexion. The knee angle is measured from the shank to the thigh; when standing, it is about 180° and decreases during flexion. Finally, the hip angle is measured from the thigh to the pelvis; when standing, it is about 180° and decreases during flexion. An illustration of the join angles is presented in Fig. 4.

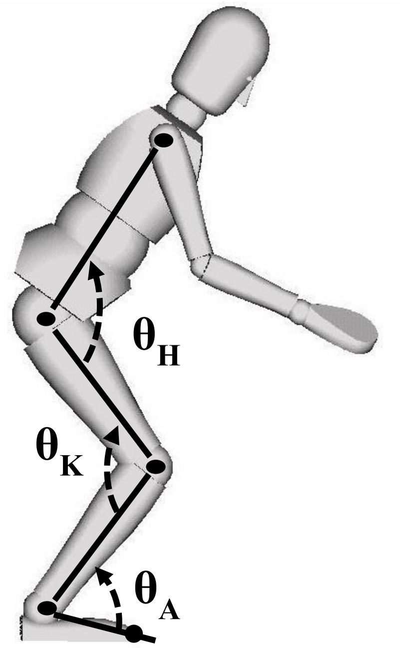


Figure 4. An illustration of the joint angles. θ_H is the hip angle, θ_k is the knee angle, and θ_A is the ankle angle.

The motion of the subjects and the ground reaction forces were filtered by using two fourth-order Butterworth low-pass filters with 10 and 35 Hz cutoff frequencies, respectively. EMG recordings were digitized by using a bandpass filter (20–450 Hz) and processed in Matlab (Math Works Inc., Cambridge, MA, USA) to obtain a linear envelope (LE). The EMG data were rectified and filtered by using a second-order low-pass Butterworth filter with 3 Hz cutoff frequency. This signal processing is based on that used in (Koo & Mak, 2005; Lenzi et al., 2012; Rose, 2014) and presented in Fig. 5.

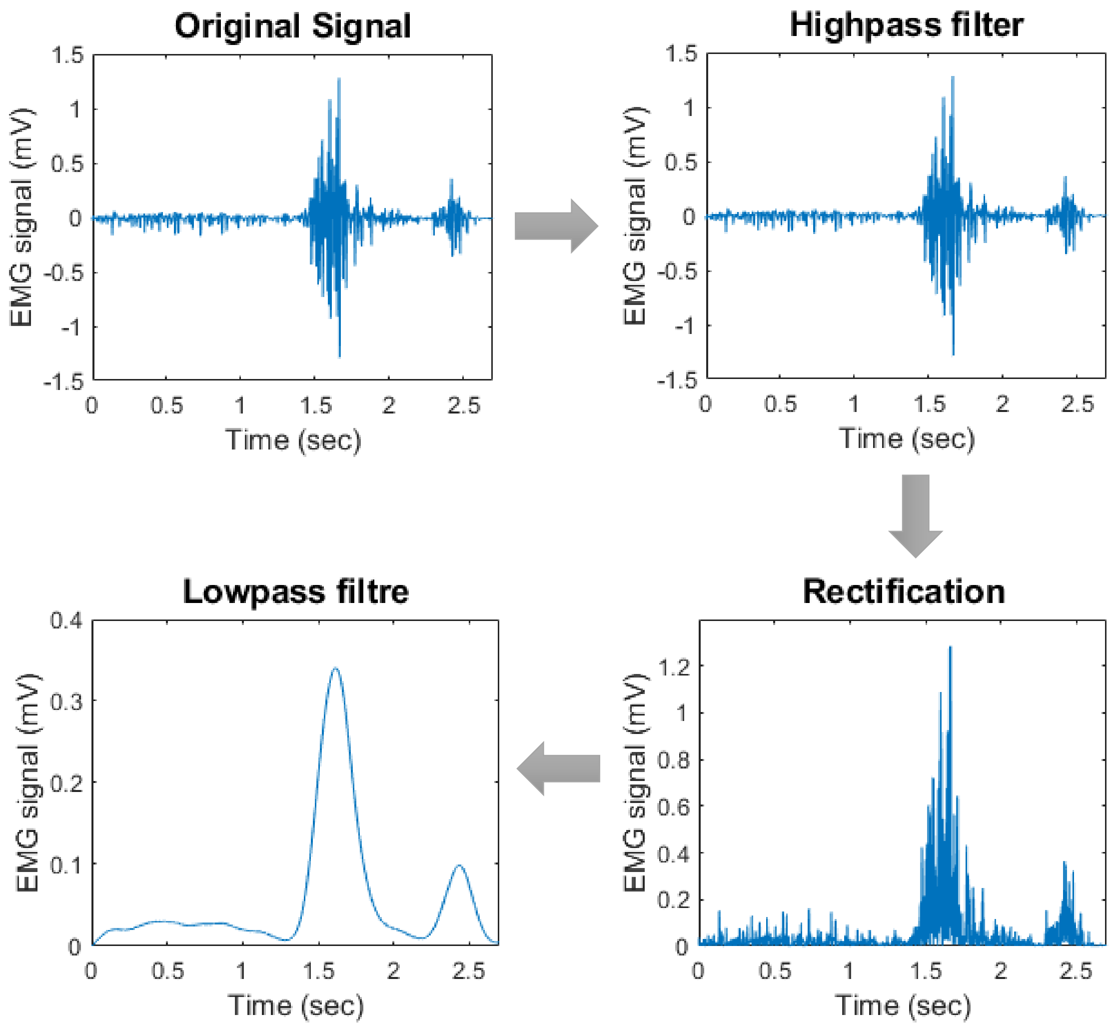


Figure 5. The stages of filtering EMG signal. The rectification and lowpass filter phases are part of the liner envelope method for signal processing.

Matlab was used to calculate the height, kinetic, and kinematic parameters. The maximum (minimum) height ΔH_{max} (ΔH_{min}) is defined as the difference between the standing COM and the maximum (minimum) height of the COM (see Fig. 3). Specifically,

$$\Delta H_{\text{max}} = H_{\text{max}} - H_{\text{standing}} \qquad (1)$$

$$\Delta H_{\text{min}} = H_{\text{standing}} - H_{\text{min}} \qquad (2)$$

where H_{standing} is the height of the COM while standing, H_{max} is the maximum height of the COM during the flight phase of the jump, and H_{min} is the minimum height of the COM during the pre-jump squat.

Next, we calculated the net mechanical work performed by the ankle, knee, and hip joints from the start of upward movement (UPM) to take-off (TO):

$$\mathrm{W_j} = \int_{\mathrm{UPM}}^{\mathrm{TO}} P_j dt = \int_{\mathrm{UPM}}^{\mathrm{TO}} M_j \dot{\omega}_j dt \qquad (3)$$

where P_j is the power at joint *j*, M_j is the moment at joint *j*, and $\dot{\omega}_j$ is the angular velocity at joint *j*. The UPM point is defined during the minimum COM obtained in the jump, H_{min}, and the TO point is defined as the point where the ground reaction force first goes to zero. The total knee power and work have exoskeleton and biological contributions. The exoskeleton power was calculated by using a model that predicts the moment provided by the exoskeleton (based on experiment and theory) multiplied by the measured angular velocity (for details, see Appendix B):

$$\mathrm{W_{Exo}} = \int_{\mathrm{UPM}}^{\mathrm{TO}} P_{\mathrm{Exo}}\, dt = \int_{\mathrm{UPM}}^{\mathrm{TO}} M_{\mathrm{Exo}} \dot{\omega}_{\mathrm{knee}}\, dt \qquad (4)$$

The biological-knee power obtained by subtracting the exoskeleton power from the total knee power is given by

$$\mathrm{W_{BioKnee}} = \mathrm{W_{totaltKnee}} - \mathrm{W_{Exo}} \qquad (5)$$

The maximum EMG of the rectus femoris and gastrocnemius muscles was determined for each jump, and the maximum muscle activity for each jump was normalized by the average maximum muscle activity of the control conditions (i.e., NoExo for the first session and NoExoS2 for the second session).

Finally, we calculated jump duration from upward movement (UPM) to take-off (TO).

2.6 Statistics

Given that the subjects had different physical traits and jumping techniques, we used a Linear Mixed Model (LMM), with the subject as a random effect, across all jumping conditions (i.e., NoExo, Exo0, Exo1, Exo2, NoExo2, NoExoS2, and Exo2S2) to examine how the exoskeleton affects jumping height. The linear mixed model was also conducted on the following parameters: (i) work performed by the joints and the exoskeleton, (ii) muscle activity, (iii) joint angles, (iv) $\Delta H_{\min}$, and (iv) jump duration. In addition, Q-Q plots ensured that the residuals of the models are normally distributed. Pairwise comparisons were conducted using Tukey's honestly significant difference test, with a significance level of 0.05. Statistical analysis was done by using R-studio, Ver 1.1.463 (R Ver 3.5.1; RStudio, Inc. Boston, MA, USA).

3. Results

3.1 Height

To examine the effect of the different experiment conditions on vertical jumping height, we defined the difference of COM height from standing to maximum COM during the jump as the jump height, ΔH_{max} (Fig. 6). By examining the height gained by each of the conditions, of the first session, with the exoskeleton (i.e., Exo0, Exo1, and Exo2) it is noticeable that as spring stiffness increased, so did the height of the jump (P<0.05). However, there was no significance difference between NoExo and Exo2. In the second session it can be seen that training with the exoskeleton (Exo2S2) contributed to significantly higher jump than all other conditions (P<0.0001). The average ΔH_{max} in Exo2S2 is 45.9±7.3 cm (mean$\pm$ SD), which is higher by 2.7$\pm$0.4 cm and 8.1$\pm$0.4 cm (mean$\pm$ SE) than in NoExoS2 and Exo0, respectively (i.e., 6.4% and 21.4% higher, respectively). Furthermore, we tested if there was a change in the subjects' vertical jumping ability between the two experimental sessions and found no significant difference between the conditions without the exoskeleton at the beginning of the sessions (NoExo and NoExoS2, P>0.05). However, there was a marginally significant difference between these conditions and NoExo2, that was performed at the end of the first experiment, which resulted in a lower jump height (P<0.06).

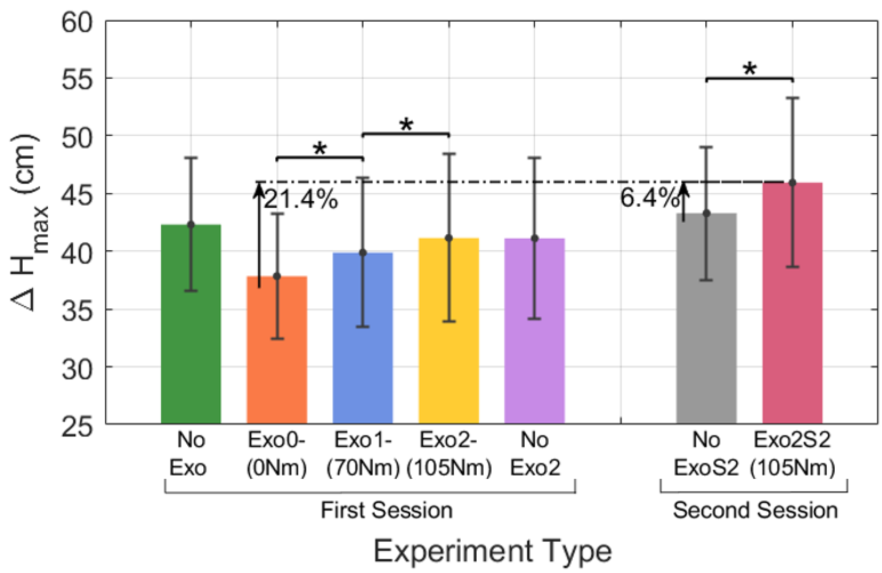


Figure 6. Max jump height relative to standing, for each of the 7 conditions. Averaged across subjects. Error bars are SD and *P $\leq$ 0.05.

The results show that eight out of the ten subjects jumped higher with the exoskeleton (Exo2S2) than without the exoskeleton (NoExoS2), as detailed in Fig. 7.

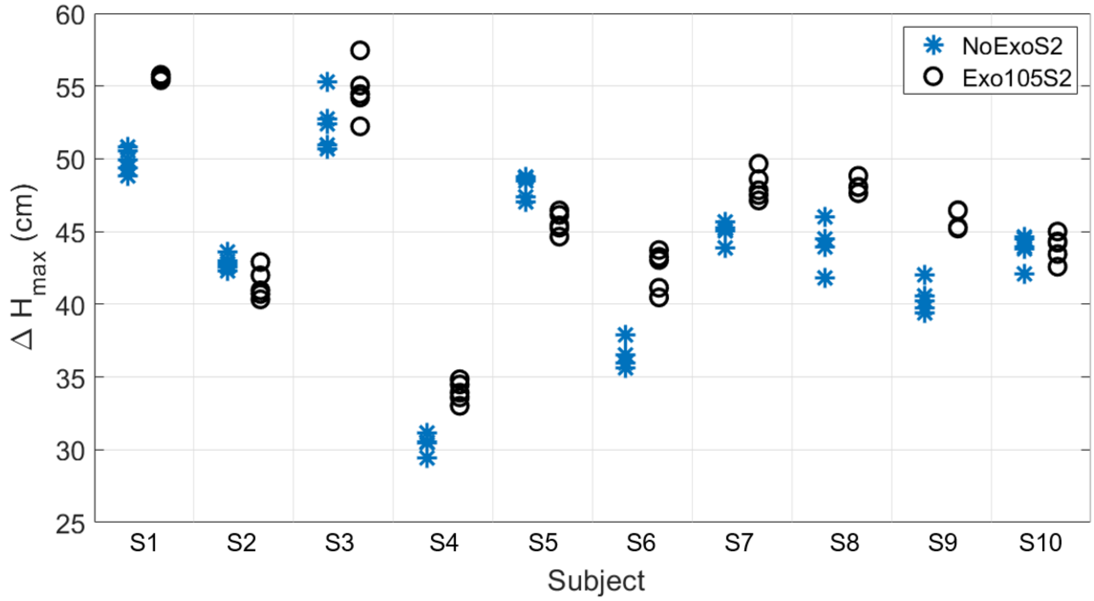


Figure 7. ΔH_{max} for each subject for conditions NoExoS2 and Exo2S2, each subject jumped 5 times in each condition

3.2 Work at joints

To gain better understanding on these results we used the data from the inverse dynamics analysis for four conditions: Exo0, Exo2, NoExoS2, and Exo2S2. First, we calculated the joint work performed by the ankle, knee, and hip as shown in equation (3), for both legs together. We also calculated the net biological knee work and net exoskeleton work (Fig. 8). The total joints and exoskeleton work at the Exo2S2 condition, 680.6±90.8 J, was the largest compare to all other conditions (P<0.0001). It was larger by 141.6±9 J and 140.5±9 J (mean± SE) than in NoExoS2 and Exo0, respectively. Also, the total knee work (i.e., exo+bio) at Exo2S2 was larger than in all other conditions (P<0.0001). Additionally, all the conditions with the exoskeleton caused an increment in hip work relative to NoExoS2 condition (P<0.1, marginally significant). Further, the hip work was the largest in Exo2S2 condition compare to all other conditions (P<0.0001).

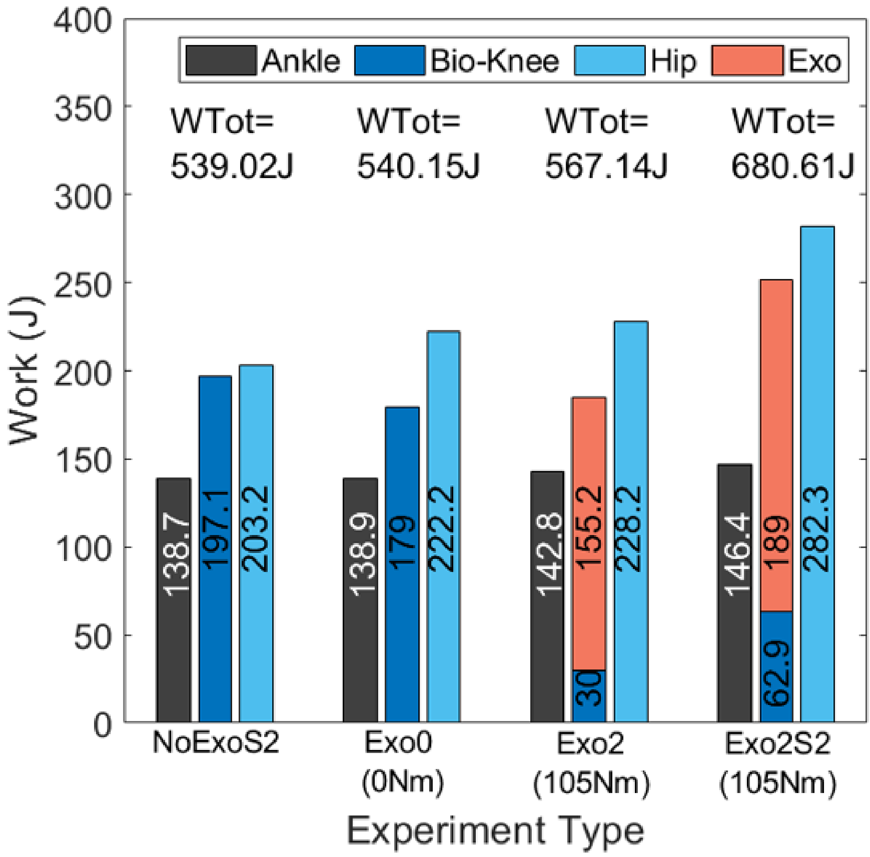


Figure 8. The work of the exoskeleton and biological knee, the ankle, and the hip joints from upward movement (UPM) to take-off (TO), for NoExoS2, Exo0, Exo2, and Exo2S2 conditions, both legs. Averaged across subjects.

3.3 Angle, Moment, and Power

We compared between NoExoS2, and Exo2S2 conditions using the profiles of the angle, moment, and power at the ankle, total knee (i.e., bio+exo), and hip. We examined these parameters from upward movement (UPM) to take-off (TO), and normalized this phase in the motion to 100% so that the results from the two conditions will be on the same scale (Fig. 9). Due to symmetry, the presented data are from the right leg only. The moments and powers were normalized by the subject's mass and height. The comparison shows that the trajectories of the joints angle, moment, and power are similar in shape. Full data of an example of a subject's jump from standing to TO, is presented in Fig. 10. It can be seen that for condition Exo2S2, the subject reaches a squat position and searches for the right position for several seconds until the start of upward movement. Therefore, although we did not intend to train the subjects with a specific jumping strategy (i.e., squat or countermovement), their jump is more like a squat jump as opposed to a countermovement without the exoskeleton. That change in jumping technique was detected for most of the subjects. Note that the normalized time is calculated differently than in Fig. 9.

Further, quantitative information on the average joints' angle during UPM point for NoExoS2, Exo0, Exo2, and Exo2S2 conditions is presented in Table 2. It can be seen that at the UPM point, the angles at the knee and hip during Exo2S2 are smaller than NoExoS2, indicating greater joints flexion ($P<0.0001$).

Table 2

Average Joint Angles at UPM Point

	NoExoS2	Exo0	Exo2	Exo2S2
Squat Angle (deg)				
Ankle	78.0 ± 5.8	79.0 ± 8.2	78.8 ± 58.2	80.2 ± 8.1
Knee	71.1 ± 15.4	74.5 ± 15.9	77.4 ± 16.5	59.2 ± 9.2
Hip	48.9 ± 18.0	47.5 ± 23.1	44.9 ± 21.0	35.2 ± 10.0

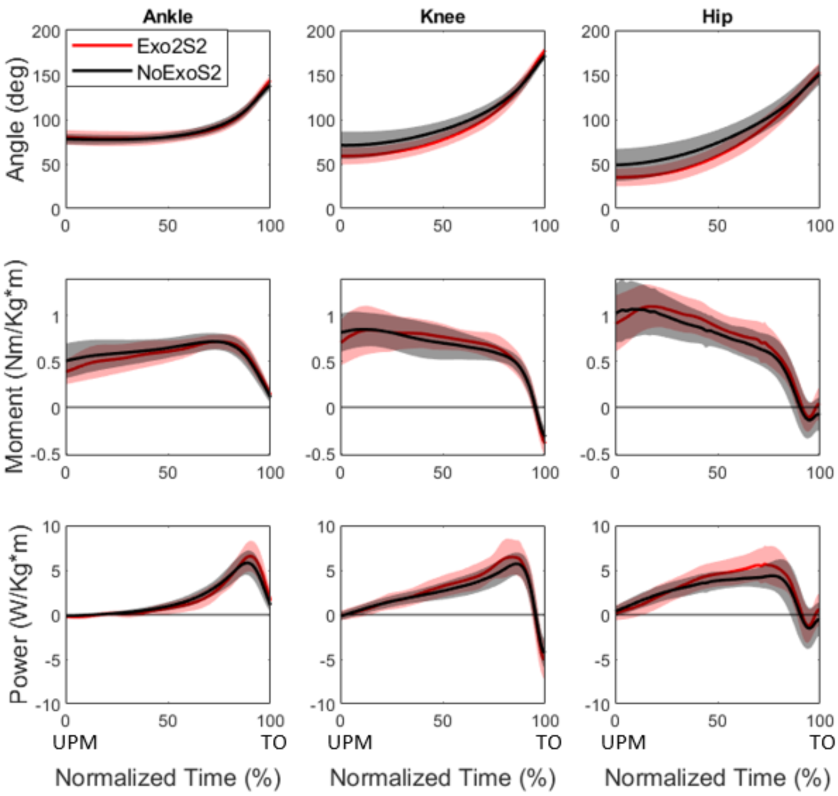


Figure 9. The angle, moment, and power at the ankle, hip, and total knee (i.e., bio+exo), during NoExoS2 and Exo2S2 conditions, from upward movement (UPM) to take-off (TO), for right leg. The average (for all subjects last 5 jumps at each condition) is the solid line and the shaded areas are the SD.

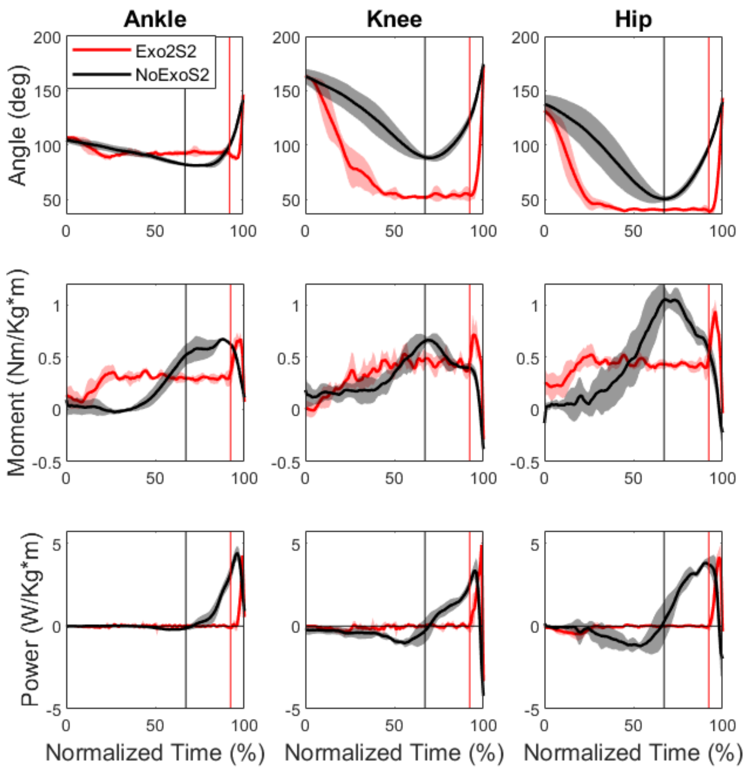


Figure 10. Angle, moment, and power of ankle, total knee (exo+bio), and hip from standing to take-off (TO), of one subject (Average± SD of five jumps), right leg. The vertical lines represent the start of upward movement (UPM) for each jumping condition.

3.4 EMG

Last, a comparison between normalized EMG peak signals was conducted in Exo0, Exo2, NoExoS2, and Exo2S2 conditions and presented in Fig. 11. The Rectus Femoris EMG peak signal was not statistically different (P>0.4). However, the Gastrocnemius EMG peak in all expect one conditions where the same. Were the signal during Exo2S2 was the largest compare to all other conditions (P<0.01), and specifically greater by 12.7$\pm$ 0.2% than during NoExoS2. The EMG signal is examined from standing (0.25 seconds before UPM) to maximum jump height, and normalized this phase in the motion to 100% so that the results from the four conditions will be on the same scale.

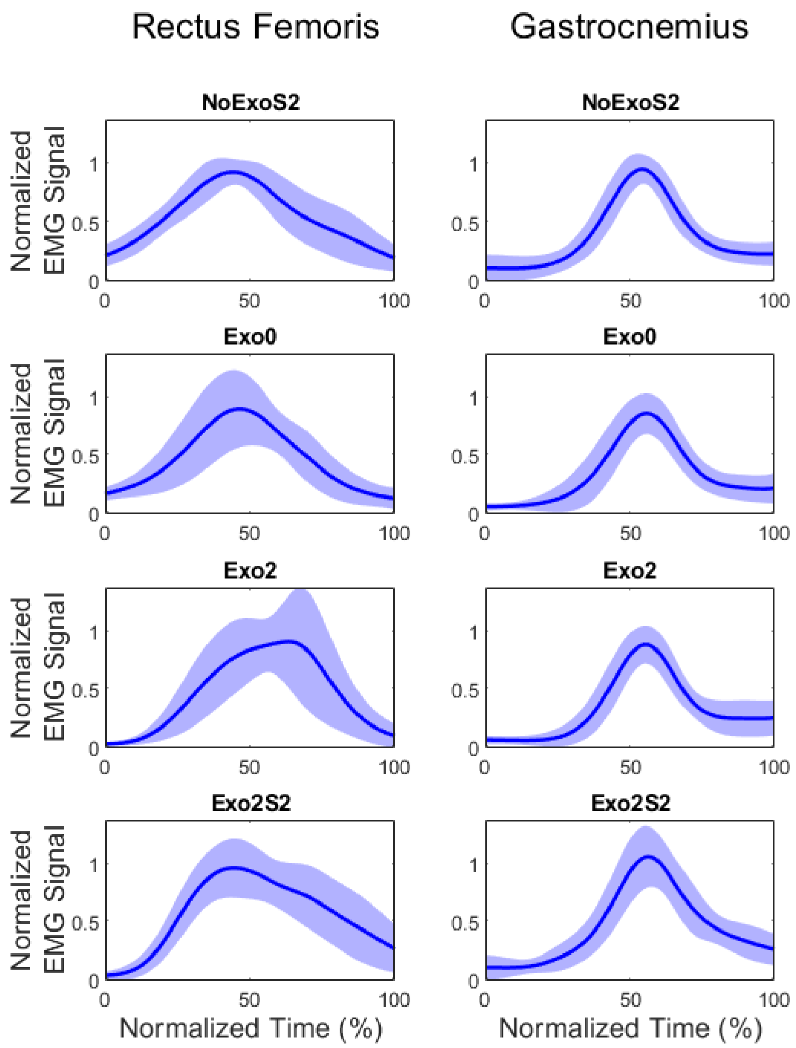


Figure 11. The normalized EMG signals of Rectus Femoris and Gastrocnemius during NoExoS2, Exo0, Exo2, and Exo2S2 conditions. The solid line is the average (for all subjects last 5 jumps at each condition), and the shaded areas are the one standard deviation.

3.5 Duration of the jump and Minimum COM

The differences of the COM from standing to minimum COM height (ΔH_{min}), and the duration of the jump from the start of upward movement (UPM) to take-off (TO), are presented in Table 3 for all experimental conditions.

It can be seen that at the UPM point, the lowest COM height obtained (i.e., larger ΔH_{min}), relative to the other conditions, was at Exo2S2 ($P<0.02$). Also, the ΔH_{min} during NoExo2 was greater than in all the other conditions, meaning lower COM height ($P<0.05$). Finally, the duration of rising from UPM to TO was the longest for Exo2S2 and NoExo2 compared to all other conditions ($P<0.05$).

Table 3
The Jump Duration and the Minimum COM for Each Condition

	NoExo	Exo0	Exo1	Exo2	NoExo2	NoExoS2	Exo2S2
ΔH_{min}(CM)	36.5±11.1	35.2±8.0	35.8±8.0	35.2±7.4	41.3±7.3	37.9±8.2	44.6±4.4
Time (sec)	0.31±0.08	0.34±0.07	0.35±0.06	0.34±0.05	0.37±0.06	0.33±0.05	0.37±0.05

4. Discussion

The results show that, after training to jump with the exoskeleton, the subjects increased their jump height by 6.4% compared to jumping without the exoskeleton. To the best of our knowledge, this is the first study that demonstrates that an exoskeleton can augment the fast, explosive jumping movement.

A major factor in improving the jump height is the dipper squat position. Although studies show that the squatting position does not affect jump height (Domire & Challis, 2007; Selbie & Caldwell, 1996), these studies were conducted without an exoskeleton. In this study, the subjects increased knee flexion to achieve the dipper squat position, which results in more energy being stored in the springs. In addition, the hip angle is smaller (i.e., greater hip flexion) at the start of the upward movement, which also corresponds to a lower COM. The changes in the hip joint might be explained by the need for the subjects to avoid falling backward. The changes in ΔH_{min} and in the joint angles are also reflected in the net work done by the joints. The total knee work and hip work increases when using the exoskeleton, where part of this additional energy is required just to raise the COM back to H_{standing}. Furthermore, the duration of time rising from the squat position to take-off was longer with the exoskeleton (Exo2S2) than without it (NoExoS2) due to the lower squat position. However, while examining the COM height during squat at Exo2S2 and NoExo2, we can see that the COM height was lower at Exo2S2 while the rising duration was the same. Hence, the dipper squat position without the exoskeleton was not efficient, but when using the exoskeleton, the dipper squat position contributed to a higher jump.

Using the device had an impact in the short term but not in the long term. This can be observed by examining the conditions without the exoskeleton at the beginning of sessions (NoExo and NoExoS2) and the end of the first session (NoExo2). There were marginally significant jump height changes. Jumping right after using the exoskeleton (NoExo2) resulted in lower jump height, while jumping without exoskeleton after three months (NoExoS2) did not lead to decreased jump height relative to NoExo. The changes in NoExo2 were reflected in lower COM during squat position. These movement changes are probably due to getting used to jumping with the device and its restrictions, and therefore did not fully reach motor adaptation for jumping without a device.

Comparing the total joint work and the maximum height difference between condition of exoskeleton with no springs (Exo0) and condition with highest spring stiffness (Exo2S2), we aim to gain a better understanding of the human-exoskeleton interaction. We analyze the energy balance, where each jump has two energy components: one to move the COM from the lowest point (UPM) to standing, and another to move the COM from standing to maximum height. If we assume no energy loss, then the difference in joint work between the two conditions Exo2S2 and Exo0 may be formulated as

(6)

$$\Delta W = mg(\Delta H_{\mathrm{min,2}} + \Delta H_{\mathrm{max,2}}^{\mathrm{p}}) - mg(\Delta H_{\mathrm{min,0}} + \Delta H_{\mathrm{max,0}})$$

$$\Delta H_{\mathrm{max,2}}^{\mathrm{p}} = \frac{140.5}{76g} - 0.43 + (0.34 + 0.38) = 0.469\ \mathrm{m} = 46.9\ \mathrm{cm}$$

where $\Delta H_{\mathrm{max,2}}^{\mathrm{p}}$ is the predicted height when using the exoskeleton, ΔW is the difference in total joint work between the two jumping conditions, and m is the average mass of the subject (73 kg) plus the exoskeleton (3 kg) for a total of 76 kg. Recall that ΔH_{min} is the difference between the COM height when standing and the minimum COM height (when squatting), and ΔH_{max} is the difference between the COM when standing and the maximum COM height (in flight). Note also that the subscripts 2 and 0 refer to Exo2S2 and Exo0, respectively. In this analysis, the jump height $\Delta H_{\mathrm{max,2}}^{\mathrm{p}}$ is predicted by using the other work parameters and the other heights obtained from the experiments. Based on the experimental results for condition Exo0, the expected height for conditions Exo2S2 is 46.9 cm, whereas the actual height gained is 45.9±7.3 cm (mean ± SD). This confirms the quality of the fit to the measurements.

Next, we examined the effect of wearing the device as a dead-weight, without the addition of spring (Exo0). Since the exoskeleton mass is 3 kg, extra energy is required to raise that mass when jumping. The amount of energy needed to raise that mass to the jump height reached in Exo0 is as follows:

$$W_{m_{exo}} = \Delta H_{\max,0} \cdot m_{\text{exo}} \cdot g = 0.378 \cdot 3 \cdot g = 11.1\,J \qquad (7)$$

If the participants had jumped without the exoskeleton, using that extra energy would have increased their jump height by:

$$\Delta \mathrm{H}_{Gained} = \frac{W_{m_{exo}}}{m_h g} = \frac{11.1}{73g} = 1.5\ cm \qquad (8)$$

However, the actual height difference between Exo0 and NoExo conditions is 4.5 cm, significantly greater than 1.5 cm. This difference between the expected height loss (by adding the extra mass of the exoskeleton) and the actual height difference in Exo0-NoExo might indicate that not all changes in joint work translate into different jump heights. The difference might be explained by the limitations of the exoskeleton, such as the fit of the exoskeleton to the user (recall that we used a single exoskeleton for all subjects). A misfit might result in losing work to compress the shank and thigh. A custom exoskeleton for each subject (see, e.g., Collins et al., 2015) could potentially lead to more efficient use of the exoskeleton work and, therefore, to higher jumps. Furthermore, it is possible that the exoskeleton reduces the degrees of freedom in the joint, thereby reducing the efficiency of the jump mechanics.

The exoskeleton design determined the spring moments as 70 and 105 N m to provide an additional moment equivalent to about 20% and 33%, respectively, of the peak knee moment (approximately 300 N m). These ratios are based on studies (Bobbert & van Ingen Schenau, 1988; Fukashiro & Komi, 1987; Vanezis & Lees, 2005) that used professional athletes weighing approximately 80 kg. However, the subjects in the present study were not professional athletes, their weight averaged about 73 kg, and their peak moment was approximately 200 N m (both knees together). Thus, in the second session, the spring stiffness is approximately 50% of the biological-knee capability. In this study, the second experiment (Exo2S2) shows that the total work provided by the biological knee is 25% of the total knee work, which is an improvement over the first experiment, where the biological knee contributes only 16% of the total knee work.

In addition, we compare our findings with simulated human jumping with a passive exoskeleton (Ostraich, 2020), which is based on a model with peak total biological knee moment of 320 N m. The results of the simulation predict that springs that provide approximately 50% of the maximum knee moment of the biological knee would lead to a contribution of about 35% biological work to the total knee work, which is only 10% greater than our results.

An analysis of the maximum normalized EMG signal indicates that no statistical difference exists between the rectus femoris muscle activation with and without the exoskeleton. For all the jumping conditions, the EMG signals from the gastrocnemius muscle are the same (except for Exo2S2 jumping condition for which the change is small). This means that the subjects reached their maximum capability in terms of force production, which is consistent with the findings of (Ostraich, 2020) that the muscles produce maximum force regardless of the spring stiffness. The improvement between the two experiments and the fact that the EMG reached a peak in all conditions suggest that users might be able to improve their performance if they train to jump with the exoskeleton, which might lead to a force-speed curve for the muscle (Jiménez-Reyes, Samozino, Brughelli, & Morin, 2017; Nalysis, The, & Ump, 2009).

When analyzing the difference between jumping with and without the exoskeleton, the techniques used in each case must be examined. During a vertical jump with the exoskeleton, the subjects had to find the better squat position to stretch the springs. The consequence is that they remain in the squat position for a long time relative to the time in the squat for the vertical jump without the exoskeleton. As a result, jumps without the exoskeleton were more like countermovement jumps, whereas jumps with the exoskeleton were more like squat jumps.

According to multiple studies, countermovement jumps are almost always higher than squat jumps (Bobbert et al., 1996; Fukashiro & Komi, 1987; Komi P. V & Bosco C, 1978; Van Hooren & Zolotarjova, 2017). Komi and Bosco (1978) suggested that the height increase is due to the storage and utilization of elastic energy. They claim that the tendinous tissues store elastic energy during downward movement and use the energy in the upward movement. However, several studies recently claimed that storage and utilization of elastic energy are not the main difference between countermovement and squat jumps (Anderson & Pandy, 1993; Bobbert et al., 1996; Kopper, Csende, Trzaskoma, & Tihanyi, 2014; van Ingen Schenau, 1984) since significantly more energy is lost as heat during a countermovement jump than during a squat jump. Bobbert *et al*. (1996) argue that the primary contribution of a countermovement is that it allows the muscles to build up a high level of active state and significant force before they start contracting, thereby allowing the muscles to produce more work.

Therefore, future studies should examine jumping with the exoskeleton using the countermovement strategy to better understand human-exoskeleton interactions and potentially increase the jump height.

5. Conclusion

This study presents a novel passive exoskeleton that increases vertical jumping height. The exoskeleton contains springs positioned parallel to the quadriceps femoris muscle that provides approximately 50% assistance moment for the biological knee.

The study discusses two experimental sessions. In the first session, the participants were equipped with the exoskeleton and jumped without instructions on how to use it. In this session, no significant difference was found when jumping with and without the exoskeleton. In the second session, the participants were trained on how to better use the exoskeleton by exploring different jumping techniques to increase the jump height.

The results of the second session reveal an increase in jump height of 6.4%$\pm$0.9% (mean$\pm$SE) when using the exoskeleton compared with the jump height without the exoskeleton, and an increase in jump height of 21.4% compared with jumping with a springless exoskeleton (deadweight). These results emphasize the need for training on the use of this exoskeleton to fully utilize it.

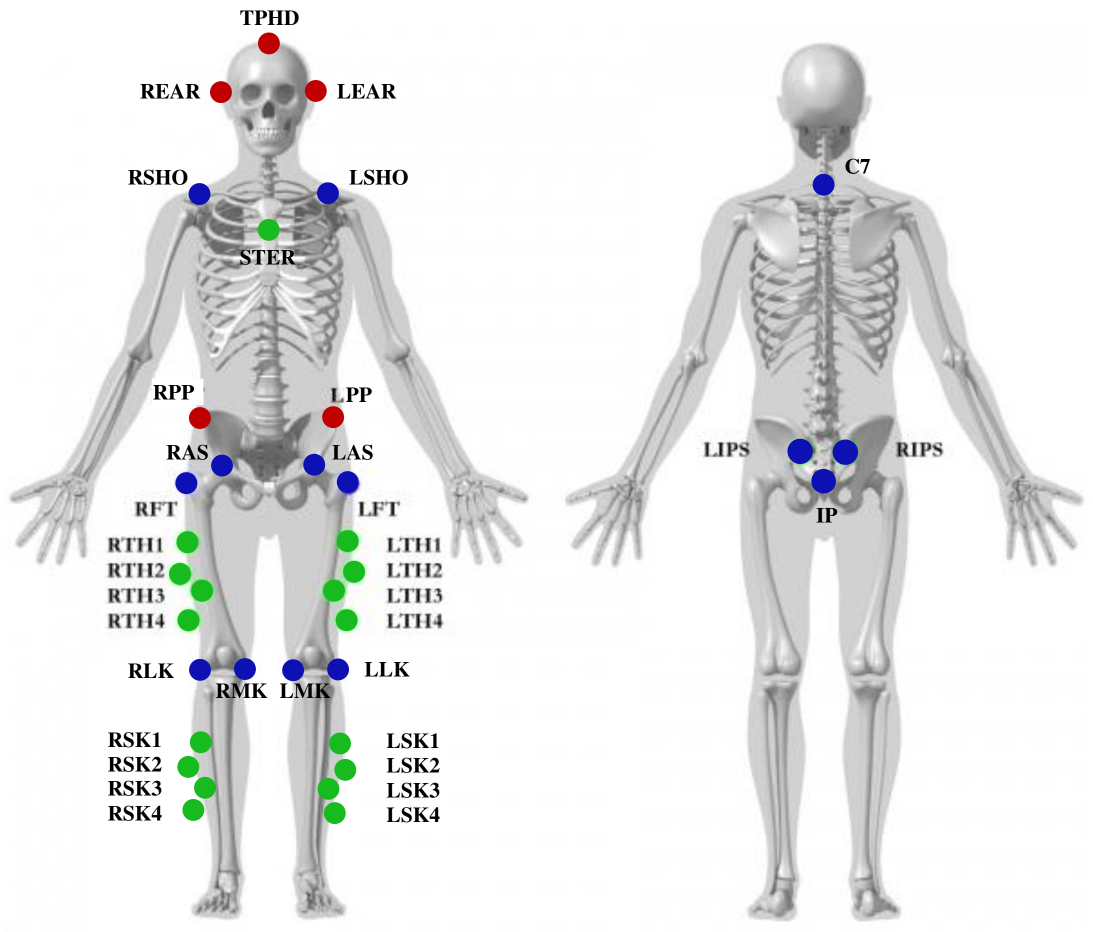
It is important to note that, to the best of our knowledge, this is the first time that using an exoskeleton improved jump height during vertical jump activity.

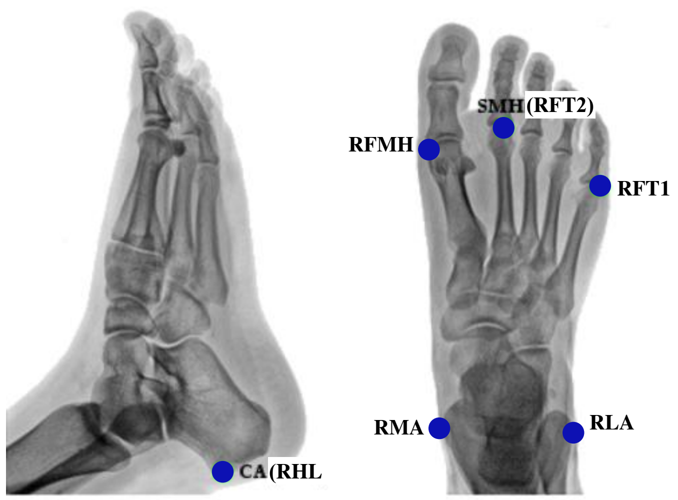
An analysis of energy balance and additional potential jumping strategies suggest that the jump height can be further improved. Thus, future studies should focus on exploring exoskeletons with better fit, additional jumping techniques including countermovement, and longer training.

6. Appendix

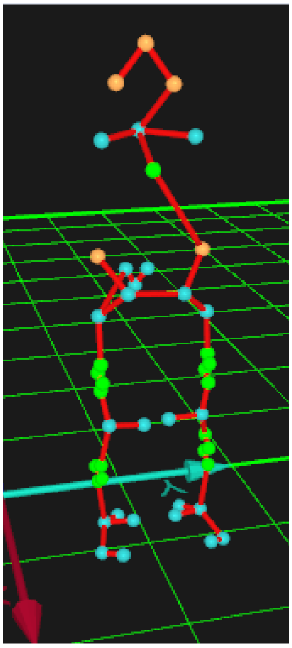
6.1 Location of the reflective markers on participant

Presented are the markers for the conditions without the exoskeleton. With the exoskeleton there are 12 more markers located on the exoskeleton (6 for each leg).


TPHD
REAR
LEAR
RSHO
LSHO
STER
C7
RPP
LPP
RAS
LAS
RFT
LFT
LIPS
RIPS
IP
RTH1
RTH2
RTH3
RTH4
LTH1
LTH2
LTH3
LTH4
RLK
RMK
LMK
LLK
RSK1
RSK2
RSK3
RSK4
LSK1
LSK2
LSK3
LSK4

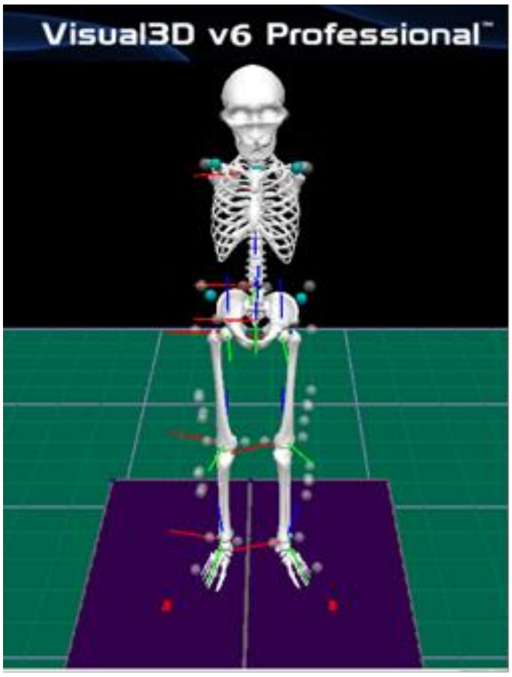

CA(RHL
SMH(RFT2)
RFMH
RFT1
RMA
RLA

6.2 AIM Model developed in Qualisys Track Manager software



The AIM Model (Automatic Marker Identification) is created from an identified file and can then be applied to any measurement that captures similar motions compared to the model.

6.3 6DoF Model built in Visual3D



This model is used to perform kinetic and kinematic calculations on each of the recorded motion files. The model files are located in the lab drive:

Coral-> lab-> JUMP-> V3D-> Barak-> Raw Data->subject file (by date)

6.4 Consent form for the first session

<u>טופס הסבר והסכמה</u>

<u>ניסוי בהערכת סיוע שלד ברך חיצוני לפעולת קפיצה אנכית</u>

חוקר אחראי: ד"ר רזיאל רימר

מנהלי מחקר: קורל בן דוד וברק אוסטרייך

המחקר נערך במחלקה להנדסת תעשייה וניהול, אוניברסיטת בן גוריון

הניסוי מיועד לגברים בלבד.

במחקר הנוכחי תתבקש לעלות על פלטת כוח ולבצע קפיצה אנכית בארבעה מצבים שונים: ללא מכשיר, עם מכשיר כאשר הקפיץ אינו מחובר, עם מכשיר ו-50% מתיחות קפיץ ועם מכשיר ו 100% מתיחות קפיץ. בכל אחד מהמצבים הנ"ל תתבקש לבצע קפיצה אנכית 5 פעמים כאשר הידיים בהצלבה על החזה. בין קפיצה לקפיצה תנוח למשך 2 דקות.

טרם ביצוע הניסוי תתבקש לבצע הליכה מהירה ומספר קפיצות במקום לצורך חימום השרירים.

הניסוי יתחיל בקפיצה ללא מכשיר, לאחר מכן ייבדקו שאר המצבים בסדר מסוים ולבסוף ייבדק שוב המצב של קפיצה ללא מכשיר.

כלומר, בסה"כ ייבדקו 5 מצבים כאשר בכל אחד מהם תבצע 5 קפיצות אנכיות. לכן, מספר הקפיצות שיתועדו הוא 25 קפיצות. בין כל קפיצה ישנה מנוחה של שתי דקות ותיעוד הקפיצה יימשך כחצי דקה. בנוסף במצבים של עם מכשיר תצטרך לבצע מספר קפיצות ניסיון על מנת להתרגל למכשיר.

הזמן של הניסוי וההכנות אליו מוערך ב- שעה וחצי.

לשרירי הרגל יחוברו אלקטרודות של EMG על מנת למדוד את פעילות השרירים, בשביל זה תתבקש לגלח חלק קטן מהשערות ברגל. כמו כן, על מנת לנתח את נתוני תנועת הגוף יחוברו מרקרים לגוף.

בנוסף, ייתכן ונבקש ממך לצלם במצלמת וידאו את תנועת הגוף במהלך ביצוע קפיצה.

במידה ותרגיש אי נעימות שמונעת ממך להמשיך בניסוי אתה רשאי להפסיק את הניסוי, אם זאת עבור ניסוי שלא מסתיים לא תקבל פיצוי כספי עבור אותו יום.

<u>כפיצוי עבור השתתפותך תקבל 50 ₪ לשעה.</u> כל פרטייך האישיים וכן תוצאות הניסוי יישארו חסויים וישמרו על גבי מחשב ייעודי במעבדת humans and robotics motions המאובטחת באמצעות קוד ואזעקה. קבצי הנתונים במחשב מוגנים והגישה לנתונים מוגבלת ותתאפשר אך ורק למנהלי המחקר ולנסיינים מורשים. פרטייך האישיים יישמרו בקובץ נפרד מתוצאותיך בניסוי.

<u>פרטים כלליים:</u>

אני החתום מטה *:

א) מצהיר בזה כי אני מסכים להשתתף בניסוי, כמפורט במסמך המפרט את חלקי הניסוי.

ב) מצהיר שהוסברו לי בפירוט כל חלקי הניסוי והסכמתי ליטול בו חלק לאחר שנענו כל שאלותיי לגבי כל אחד מחלקי הניסוי.

ג) מצהיר בזה כי הוסבר לי על-ידי: שם החוקר: (ימולא על ידי החוקר המעביר)

1) כי אני חופשי לבחור שלא להשתתף בניסוי וכי אני חופשי להפסיק בכל עת את השתתפותי בניסוי מכל סיבה שהיא.
2) במידה ואני חש ברע או באי נוחות במהלך הניסוי חובה עלי לדווח לנסיין על מנת להפסיק את הניסוי.
3) כי מובטח שזהותי האישית תשמר סודית על-ידי כל העוסקים והמעורבים במחקר ולא תפורסם בכל פרסום כולל בפרסומים מדעיים.
4) כי מובטחת לי נכונות לענות לשאלות שיועלו על-ידי.

שם פרטי ומשפחה:	
חתימה:	טלפון:

*הצהרה זו הנה סודית ואינה ניתנת להעברה או שימוש לצורך שום דבר או גורם אחר פרט לצורכי מחקר זה

תאריך ______________ חתימת מעביר הניסוי ____________

אנו מודים לך על השתתפותך במחקר.

לפרטים נוספים ניתן לפנות לקורל בן דוד בטלפון 0528021820 או בדוא"ל coralben@post.bgu.ac.il .

6.5 Consent form for the second session

<u>טופס הסבר והסכמה</u>

<u>ניסוי בהערכת סיוע שלד ברך חיצוני לפעולת קפיצה אנכית</u>

חוקר אחראי: ד"ר רזיאל רימר

מנהלי מחקר: קורל בן דוד וברק אוסטרייך

המחקר נערך במחלקה להנדסת תעשייה וניהול, אוניברסיטת בן גוריון

הניסוי מיועד לגברים בלבד.

במחקר הנוכחי תתבקש לעלות על פלטת כוח ולבצע קפיצה אנכית בשני מצבים שונים: ללא מכשיר ועם מכשיר ו 100% מתיחות קפיץ. בכל אחד מהמצבים הנ"ל תתבקש לבצע קפיצות אנכיות כאשר הידיים בהצלבה על החזה. בין קפיצה לקפיצה תנוח למשך דקה וחצי דקות.

טרם ביצוע הניסוי תתבקש לבצע הליכה מהירה ומספר קפיצות במקום לצורך חימום השרירים.

הניסוי יתחיל בקפיצה ללא מכשיר ולאחר מכן עם מכשיר ו100% מתיחות קפיץ. תצטרך לבצע קפיצות הכנה ותרגול לפני המצבים הנ"ל.

הזמן של הניסוי וההכנות אליו מוערך ב- שעה וחצי.

לשרירי הרגל יחוברו אלקטרודות של EMG על מנת למדוד את פעילות השרירים, בשביל זה תתבקש לגלח חלק קטן מהשערות ברגל. כמו כן, על מנת לנתח את נתוני תנועת הגוף יחוברו מרקרים לגוף.

בנוסף, ייתכן ונבקש ממך לצלם במצלמת וידאו את תנועת הגוף במהלך ביצוע קפיצה.

במידה ותרגיש אי נעימות שמונעת ממך להמשיך בניסוי אתה רשאי להפסיק את הניסוי, אם זאת עבור ניסוי שלא מסתיים לא תקבל פיצוי כספי עבור אותו יום.

<u>כפיצוי עבור השתתפותך תקבל 50 ₪ לשעה.</u> כל פרטיך האישיים וכן תוצאות הניסוי יישארו חסויים וישמרו על גבי מחשב ייעודי במעבדת humans and robotics motions המאובטחת באמצעות קוד ואזעקה. קבצי הנתונים במחשב מוגנים והגישה לנתונים מוגבלת ותתאפשר אך ורק למנהלי המחקר ולנסיינים מורשים. פרטייך האישיים יישמרו בקובץ נפרד מתוצאותיך בניסוי.

<u>פרטים כלליים:</u>

אני החתום מטה *:

א) מצהיר בזה כי אני מסכים להשתתף בניסוי, כמפורט במסמך המפרט את חלקי הניסוי.

ב) מצהיר שהוסברו לי בפירוט כל חלקי הניסוי והסכמתי ליטול בו חלק לאחר שנענו כל שאלותיי לגבי כל אחד מחלקי הניסוי.

ג) מצהיר בזה כי הוסבר לי על-ידי: שם החוקר: (ימולא על ידי החוקר המעביר)

1) כי אני חופשי לבחור שלא להשתתף בניסוי וכי אני חופשי להפסיק בכל עת את השתתפותי בניסוי מכל סיבה שהיא.
2) במידה ואני חש ברע או באי נוחות במהלך הניסוי חובה עליי לדווח לנסיין על מנת להפסיק את הניסוי.
3) כי מובטח שזהותי האישית תשמר סודית על-ידי כל העוסקים והמעורבים במחקר ולא תפורסם בכל פרסום כולל בפרסומים מדעיים.
4) כי מובטח לי נכונות לענות לשאלות שיועלו על-ידי.

שם פרטי ומשפחה:	
חתימה:	טלפון:

*הצהרה זו הנה סודית ואינה ניתנת להעברה או שימוש לצורך שום דבר או גורם אחר פרט לצורכי מחקר זה

תאריך ______________ חתימת מעביר הניסוי ____________

אנו מודים לך על השתתפותך במחקר.

לפרטים נוספים ניתן לפנות לקורל בן דוד בטלפון 0528021820 או בדוא"ל coralben@post.bgu.ac.il .

6.6 Health declaration for both sessions

שאלון נבדקים

	קרא בעיון וענה בכנות על השאלות הבאות: כן / לא	כן	לא	הערות
1	האם נאמר לך על ידי רופא/ה שיש לך בעיה בלב ומומלצת לך פעילות גופנית בהשגחה רפואית?			
2	האם את/ה סובל/ת מכאב או לחץ בחזה בעת מאמץ גופני?			
3	האם הופיע בחודש האחרון כאב או לחץ בחזה ללא קשר למאמץ גופני?			
4	האם אתה סובל מהפרעות בשיווי המשקל מסחרחורות או מנטיה להתעלפויות?			
5	האם אתה נוטל תרופות לאיזון לחץ דם או לטיפול במחלת לב?			
6	האם אחד מבני משפחתך נפטר מבעיות לב או מוות פתאומי לפני שמלאו לו 55שנה?			
	אם סבלת מהתחושות הבאות בחודש האחרון ענה בכנות כן / לא			
7	חולשה ועייפות			
8	הרדמות בלתי מכוונת במהלך היום			
9	סחררחורת			
10	קוצר נשימה			
11	כאבים בחזה			
12	דפיקות לב עזות או פעימה חסרה			
13	איבוד הכרה			
14	מחלת חום			
15	חולה היום או חלית במחלה אחרת במהלך החודש האחרון			
16	היה לך חום מעל 38 מעלות בשבוע האחרון			
17	אתה משתעל			
18	היית במגע קרוב עם חולה קורונה מאומת בשבועיים האחרונים			

	האם סבלת מפציעות (נקע, שבר, פריקה) , עברת ניתוח או סובל מכאבים באיברים הבאים: אם כן ציין את סוג הפציעה כאב	**כן**	**לא**	**הערות**
19	גב			
20	ירך (ימין או שמאל)			
21	ברך (ימין או שמאל)			
22	שוק (ימין או שמאל)			
	כף רגל (ימין או שמאל)			
23	קרסול (ימין או שמאל)			
24	בקע/ קילה/ שבר			
25	**שאלות כלליות**			
26	האם אתה עוסק בפעילות גופנית כגון (ריצה, הליכה, חדר כושר, התעמלות כגון חיטוב או פילאטיס, משחקים קבוצתיים (כדורגל, כדורסל, כדורעף וכו״).			
27	רשום את הגיל שלך היום (בשנים)			
28	משקל הנבדק (בק״ג)			
29	גובה הנבדק (בס״מ)			

אני החתום מטה: מצהיר בזה שהוסבר לי פרוטוקול הניסוי וכי אני מסכים להשתתף בניסוי, ואין לי בעיה בריאותית שיכולה למנוע ממני לבצע את הניסוי

שם פרטי ומשפחה:	
חתימה:	טלפון:

קריטריונים לסינון (להשאיר בידי החוקרים)

אם ענה כן על אחת משאלות 1-15 לא יכול להשתתף בניסוי!!!

בנוסף ענה כן על אחת מהשאלות 16 עד 22 .יש לברר מתי הייתה הפציעה

- **במקרה של פריקה לא יכול לעשות את הניסוי**
- **במקרה של נקע פחות משלושה חודשים מהניסויי , לא יכול להשתתף.**
- **במקרה של שבר פחות משישה חודשים מהניסויי , לא יכול להשתתף.**
- **במקרה של קילה (שאלה 22) אם לא בוצע ניתוח לא יכול להשתתף בניסוי, אם בוצע ועברה שנה לפחות יוכל להשתתף.**
- **אם סובל מכאבים באיבר / מפרק כלשהוא ולא מדובר כאבים כתוצאה מפעילות גופנית שהתבצעה בימים לפני הניסויי (כגון התכווצות שרירים) גם לא יבצע את הניסויי.**
- **אם גיל (שאלה 24) המשתתף יותר מ 35 אז הוא לא יכול להשתתף .**
  - **(לפי ארצות הברית עד גיל 40 לא צריך אישור) ללא אישור מרופא שמותר לו לבצע פעילות גופנית (לדוגמא חדר כושר).**
  - **לפי הצעה של איגוד הקרדיולוגים עד גיל 46 אפשר לעסוק בפעילות ספורטיבית אם ענו על שאלות 1-6 בשלילה.**

6.7 Receipt

קבלה

הנני מצהיר/ה כי השתתפתי כנבדק במחקרו של החוקר ____________________ .

עבור השתתפותי כנבדק במחקר קבלתי (נא לסמן במקום המתאים):

☐ שוברי מתנה בשווי של ______ ש"ח כ"א - סה"כ _________ ש"ח.

☐ מתנה אחרת : ___________________________ (נא לפרט).

הנני מצהיר/ה כי בשנת המס הנוכחית:

☐ קבלתי גמול מסוג זה בסך ________ ש"ח

☐ לא קבלתי גמול מסוג זה בגין השתתפות במחקר זה או אחר באוניברסיטה.

ידוע לי כי קבלת גמול זה בגין השתתפותי במחקר אין משמעותה קיום יחסי עובד- מעביד ולא תהיה לי כל תביעה בהקשר זה .

שם: ___________________ ת.ז. _________________

חתימה __________________ תאריך _______________

6.8 Procedure for running Matlab files

הגישה לכל הקבצים היא דרך הדרייב של המעבדה.

קבצי הנתונים הגולמיים נמצאים בכתובת הבאה:

Coral-> lab-> JUMP-> V3D-> Barak-> Raw Data

קבצי C3D אלו הקבצים שיצאו מתוכנת QTM. קבצי המטלב אלו הקבצים לאחר שעברו עיבוד בתוכנת V3D.

שמות הקבצים מעידים על סוג הקפיצה:

בלי מכשיר-

- DD.M_static קובץ סטטי להרצה בתוכנת V3D
- DD.M_jTry1 קפיצת ניסיון
- DD.M_j1 מדידה של קפיצה אחת ללא מכשיר
- DD.M_static2 קובץ סטטי עבור תנאי NoExo2

עם מכשיר-

- DD.M_Bstatic קובץ סטטי להרצה בתוכנת V3D
- DD.M_B0_Try1 קפיצת ניסיון עם מכשיר בלי קפיץ
- DD.M_B0_j1- מדידה של קפיצה אחת עם מכשיר ללא קפיצים

  כאשר יש שני קפיצים (Exo1) אז באמצע יהיה כתוב B1

  כאשר יש שלושה קפיצים (Exo2/Exo2S2) באמצע יהיה כתוב B2.

את קבצי ה C3D מריצים בתוכנת V3D באופן הבא:

עם שלד חיצוני:

- לפתוח pipeline-> ללחוץ על open pipeline-> תחת תיקיות Jump -> V3D לבחור את הקובץ JUMP
- ללחוץ על execute pipeline
- עכשיו צריך לבחור קבצי ניסוי. לגשת לV3D -> barak -> Raw Data -> exo -> ולבחור את כל קבצי הניסוי חוץ מהסטטי
- עכשיו יבקש לבחור סטטי. יש רק סטטי אחד לכל הקבצים עם המכשיר- בוחרים אותו (באותה תיקייה של שאר הקבצים).
- אחרים כך מתבקשים לבחור את המודל (גם באותה תיקייה)
- מזינים משקל, גובה ובוחרים את כל קבצי הניסוי
- שומרים את זה בשם שבוחרים
- כל הקבצים של המטלב יוצאים לתוך התיקייה של התאריך (יידרסו אחד את השני אם נעשה כמה פעמים).
- מעתיקים את הקבצים האלה לתוך תיקיה שבה מריצים את הקוד מטלב תחת: JUMP-> V3D-> barak -> analysis

  ושם שומרים לפי תאריך הקפיצה

בלי שלד חיצוני:

- לפתוח pipeline-> ללחוץ על open pipeline-> תחת תיקיות Jump <- V3D<- barak<- Raw <- data<- without לבחור את pipeline_jump_without
- מודל נמצא תחת without ונקרא model without
- כל השאר אותן הנחיות כמו עם מכשיר

אחרי שסיימנו להריץ מעתיקים את קבצי המטלב שיצאו לתוך תיקיות תאריכי הניסוי הנמצאות בכתובת הבאה:

Coral-> lab-> JUMP-> V3D-> Barak-> analysis -> First part

Second part

Combination of parts

בתיקיות First part ו- Second part נמצאות תיקיות של כל תאריכי הניסוי ותיקיית ניתוח נתונים עבור כל המשתתפים. First part זה בשביל החלק הראשון של הניסוי ו Second part בשביל החלק השני.

בתיקיות לפי תאריכי הניסויים מוציאים את כל הנתונים הדרושים לאותו נבדק באמצעות הקבצים הבאים:

- AnalysisCOM- הוצאת נתונים על גובה קפיצה, מינימום מרכז מסה, משך זמן הקפיצה ומהירות מרכז מסה בניתוק .
- workAnalysisv5- הוצאת נתונים על עבודה במפרקים, מומנט מקסימלי והספק מקסימלי.
- KneePlot_v3- הוצאת נתונים לתרשים זווית-מומנט-הספק (עבור כל אחד מהמפרקים)
- AngleAnalysis- הוצאת נתונים על הזווית במפרקים בזמן UPM
- בתוך תיקיית EMGfile נשתמש בקובץ EMGAnalysisPersub_v3- הוצאת נתונים על סיגנל הEMG.

בכל אחד מהקבצים הנ"ל נדרש רק להריץ את הקוד והנתונים נשמרים אוטומטית לתיקייה של תאריך הניסוי.

את הנתונים הללו נעתיק לתוך תיקיות הנתונים של כל המשתתפים (נמצאת באותו מקום של כל התיקיות עם תאריכי הניסויים) בשם all subjects. תיקייה זו מכילה סיכום נתונים עבור כל המשתתפים לחלק הנתון: זוויות, עבודה במפרקים, EMG, גבהי מרכז מסה ועוד. בכל אחת מהתיקיות (לאחר שהעתקנו את הנתונים הרלוונטים מכל תיקיות התאריכים) נריץ את קובץ הקוד ונקבל סיכום של ממוצע+סטיית תקן וטבלה המכילה את תוצאות כל הקפיצות עבור כל הנבדקים (אין צורך לשנות דבר אלא רק להריץ).

תיקיית Combination of parts :

מכילה את כל הקודים ליצירת כל הגרפים והטבלאות המופיעים בתזה.

כל הנתונים שהוצאו מתיקיית allsubjects בשני החלקים מרוכזים לתוך טבלה אחת שמכילה את כל הנתונים ונקראת main_v7. בטבלה זו ניתן למצוא את כל הנתונים עבור כל נבדק ועבור כל אחת מהקפיצות של הנבדק.

עבור כל אחד מהגרפים צריך להיכנס לתיקייה המתאימה ופשוט להריץ את הקוד (גרף מומנט זווית הספק למשל ניכנס לתיקיית angle_moment_power).

בכדי לבצע את הניתוחים הסטטיסטיים נפתח את קובץ R_analysis. בקובץ זה נבחר להזין את טבלת הנתונים שלנו main_v7. הקובץ מחולק לפי המשתנים השונים (גובה קפיצה, עבודה במפרקים וכו..) כל חלק כזה יש להריץ בנפרד שורה שורה בכדי לקבל את מודל LMM, לוודא את הנחות המודל, למצוא ממוצעים של הנתונים ואת ההבדלים הסטטיסטיים בין הקטגוריות.

על מנת למצוא מידע מפורט יותר על קבצי המטלב ניתן להיכנס לתיקייה הבאה:

Coral-> lab-> JUMP-> ניסויים- טפסים מעקב והוראות

ההסבר על הקבצים יהיה תחת קובץ "קבצי מטלב לניסוי קפיצה אנכית עם שלד חיצוני".

בתיקייה זו ניתן גם למצוא את פרטי הנבדקים (תאריכים, משקל, גובה והערות) תחת קובץ "מעקב ניסויים".

בחלק השני של הניסוי, בכדי לבחון את מידת השיפור של אימון הנבדק, ביצעתי שיערוך של גובה הקפיצה. לאחר כל קפיצת אימון מצאתי ידנית את הפריים בו גובה הקפיצה היה הגבוה יותר ודגמתי את המרקרים שממוקמים על הכתפיים (בתוכנת QTM). הגובה הממוצע של הכתפיים שימש לשערוך גובה קפיצה ובכך ניתן היה לדעת האם הטכניקה החדשה סייעה לשיפור גובה הקפיצה ובכמה בערך.

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תקציר

מחקרים אחרונים הראו כי שלדים חיצוניים יכולים לשפר את תנועתיות האדם ולסייע בביצוע פעולות יומיות כמו הליכה, ריצה או דילוג. רוב השלדים החיצוניים תוכננו להפחית את המאמץ (צריכה מטבולית) המבוצע על ידי המשתמש תוך ביצוע פעולות אירוביות. אולם, שלדים חיצוניים המסייעים בפעולות של כוח מהיר-מתפרץ, ובאופן ספציפי קפיצה אנכית, לא נחקרו מספיק לעומק. יתר על כן, ישנו עדיין חוסר הבנה מהותי בנוגע לאינטראקציה שבין האדם לשלד החיצוני.

ההשערה העיקרית שהייתה לנו היא ששלד חיצוני פסיבי יוכל להגדיל את גובה הקפיצה האנכית מבלי לספק אנרגיה חיצונית נוספת. השלד החיצוני הפסיבי ממוקם באזור הברך ומכיל קפיצים הפועלים במקביל לשריר הארבע ראשי. קפיצים אלו אוגרים אנרגיה בשלב העבודה השלילית, במהלך כיפוף הברך, ומחזירים את האנרגיה בשלב העוקב שהוא שלב של עבודה חיובית, במהלך יישור הברך. האנרגיה שנאגרה יכולה באופן זה לגרום לקפיצה גבוהה יותר.

השלד החיצוני נבדק על עשרה נבדקים בריאים, בשני חלקי ניסוי נפרדים, בהם הנבדקים שאפו לקפוץ הכי גבוה שהם יכולים. בחלק הראשון, הנבדקים קפצו תחת חמישה תנאי ניסוי- שניים בלי השלד החיצוני ושלושה עם השלד החיצוני בשלוש רמות נוקשות שונות של הקפיצים. הנבדקים קפצו בלי לקבל הנחיות על איך להשתמש בשלד החיצוני באופן מיטבי. התוצאות הראו עלייה בגובה הקפיצה ככל שרמת הנוקשות של הקפיץ עלתה, אולם לא היה הבדל בין גובה הקפיצה עם השלד החיצוני ובלעדיו. בחלק השני, הנבדקים קפצו תחת שני תנאי ניסויי- בלי שלד חיצוני ועם שלד חיצוני ברמת נוקשות הקפיץ הגבוהה ביותר. הנבדקים עברו אימון בכדי לנצל טוב יותר את יכולות השלד החיצוני, זאת על ידי בחינה של מספר טכניקות קפיצה שמטרתן לשפר את האדפטציה לשלד החיצוני.

החלק השני של הניסוי, אשר כלל הנחייה ואימון של הנבדקים לשימוש מיטבי בשלד החיצוני, הניב גובה קפיצה רם יותר ב $6.4\% \pm 0.9\%$ (ממוצע ± שגיאת תקן) לעומת קפיצה ללא השלד החיצוני. למיטב ידיעתנו, זאת הפעם הראשונה ששלד חיצוני פסיבי הצליח לשפר את פעולת הקפיצה האנכית. הידע שנרכש במהלך מחקר זה בנוגע לאינטראקציה שבין השלד החיצוני למשתמש, יכול פוטנציאלית לסייע בתהליכי פיתוח של שלדים חיצוניים המיועדים לפעולות של כוח מהיר-מתפרץ. בנוסף לכך, חברי המעבדה שלנו ישתמשו בתוצאות ממחקר זה לפיתוח מודל של האינטראקציה בין השלד החיצוני לאדם באמצעות שימוש בתהליך בקרה אופטימלית, אשר מטרתו לאפשר פיתוח סוגים שונים של שלדים חיצוניים בדרך מהירה וזולה יותר.

חלקים מעבודה זו הוצגו בכנס ISB\ASB 2019 בקלגרי, קנדה , ובכנס נוסף, WeRob 2020 בויגו, ספרד (וירטואלית). כעת מתבצעת הכנה של מאמר לפרסום בכתב העת המדעי Science Robotics.

מילות מפתח: אדפטציה, אוגמנטציה, שלד חיצוני פסיבי, קפיצה אנכית

אוניברסיטת בן-גוריון בנגב

הפקולטה למדעי ההנדסה

המחלקה להנדסת תעשייה וניהול

הערכה של שלד ברך חיצוני פסיבי לקפיצה אנכית

חיבור זה מהווה חלק מהדרישות לקבלת תואר מגיסטר בהנדסה

מאת: קורל בן דוד

כסלו תשפ"א נובמבר 2020

אוניברסיטת בן-גוריון בנגב

הפקולטה למדעי ההנדסה

המחלקה להנדסת תעשייה וניהול

הערכה של שלד ברך חיצוני פסיבי לקפיצה אנכית

חיבור זה מהווה חלק מהדרישות לקבלת תואר מגיסטר בהנדסה

מאת : קורל בן דוד

מנחה : דר' רזיאל רימר

חתימת המחבר ....קורל............ תאריך : 24/01/2021..................

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