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Design and Evaluation of a Passive Knee Exoskeleton for Vertical Jumping

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*Abstract*— Exoskeletons have been shown to augment human mobility and facilitate daily tasks such as walking, running, and hopping. The goal of an exoskeleton is to reduce the effort (i.e., metabolic rate) expended by its user in doing aerobics tasks. However, exoskeletons that assist fast, explosive movements, specifically vertical jumping, have yet to be thoroughly investigated. Furthermore, a fundamental lack of understanding still prevails regarding human-exoskeleton interactions. In the present work, we design and test a passive knee exoskeleton to increase vertical jumping height. The exoskeleton consists of springs acting parallel to the quadriceps femoris muscle. The jump height, the springs store energy in the negative-work phase, during knee flexion, and inject the energy in the following positive-work phase, during knee extension. This energy can then be utilized to help increase the jump height. The exoskeleton was tested on ten healthy subjects during two experimental sessions in which the subjects tried to jump as high as possible. In the first session, the subjects jumped without the benefit of instructions on how to use the exoskeleton. In the second session, the subjects were trained to better utilize the exoskeleton by exploring different jumping techniques to improve their adaption to the exoskeleton. The training with the exoskeleton in the second experiment resulted in a 6.2%0.9% (meanSE) increase in jump height compared with jumping without the exoskeleton.

*Index Terms* — Adaptation, Augmentation, Exoskeleton, Vertical Jumping

# INTRODUCTION

T

He 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.

The goal of the multiple wearable exoskeletons designed and studied in previous research is to augment walking or running by reducing the metabolic cost. Over the past decade, several studies have shown that metabolic power is reduced in walking [1]–[5] and running [6]–[8], and one study even examined an exoskeleton that assists both walking and running [9].

Sawicki *et al*. [10] 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 [9], [11], whereas passive exoskeletons use passive elements such as springs and dampers [7], [8], [12]. Nuckols *et al*. [13] 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.

The use of an exoskeleton to augment walking, running, and leaping was already proposed already in 1890 by Yagn [14], who presented a theoretical design consisting of long bow springs operating parallel to the legs. Later, Grabowski and Herr [15] 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 [16] 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*. [17] 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.

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 [18]. In addition, hip and knee joint moments have been reported to exceed ankle moments during a vertical jump [18]–[20].

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.

The goals of the study are thus to test whether a passive exoskeleton can improve vertical jumping height in order to better understand how to development exoskeletons for fast, explosive motions, and to examine human-exoskeleton interactions.

# Methods

## Subjects

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. The study was approved by Ben-Gurion University’s Human Research Institutional Review Board.

## Exoskeleton Design

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 given in Appendix A.

## 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 about walking [1], [21], which showed that the subjects adapted to the exoskeleton and that their performance improved from one session to the other.

Diagram

Description automatically generated

Fig. 1. The designed knee exoskeleton.

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 tests. 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 [18]–[20] with professional athletes, these values provide about 20% and 33% peak knee moment during the jump, respectively.

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 [22], who found that walking on rough terrain while exploring various walking speeds reduces the time for converges of the cost of transport to minimum during walking at preferred speed. In addition, in a study of human walking with exoskeletons, Selinger [23] 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 (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. The subjects were instructed to keep their feet pelvic-width apart, to the extent possible. Each subject executed up to ten training jumps so as to adapt to the new jumping technique with the exoskeleton.

Diagram

Description automatically generatedIn both sessions, the subjects followed a given warm-up routine. Then, for each jump, they were instructed to jump as high as possible with their hands crossed on their chest (see Fig. 2). To prevent fatigue, the subjects rested for two minutes between jumps. Fig. 2 shows the phases of the jump.

Fig. 2. 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.

## 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. 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 [24]–[27]. 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 using adhesive tape provided by the manufacturer. However, 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.

## Data Analysis

The data from all three systems were recorded and synchronized using Qualisys Track Manager software (Qualisys, Gothenburg, Sweden) and then exported into Visual 3D (C-Motion Inc., Rockville, MD, USA), which uses bottom-up inverse dynamics [28] with six degrees of freedom to calculate joint angles, angular velocities, body center of mass (COM), moments, and powers.

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.

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 [29]–[31].

Matlab was used to calculate the height, kinetic, and kinematic parameters. The maximum (minimum) height ( is defined as the difference between the standing COM and the maximum (minimum) height of the COM (see Fig. 2). Specifically,

(1)

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where is the height of the COM while standing, is the maximum height of the COM during the flight phase of the jump, and 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):

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where is the power at joint *j*, is the moment at joint *j*, and is the angular velocity at joint *j*. The UPM point is defined during the minimum COM obtained in the jump, , 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):

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

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Finally, 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).

## 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, and (iv) . 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).

# Results

We examined to determine how the experimental conditions affected jumping height (Fig. 3). Examination of for conditions Exo0, Exo1, and Exo2 showed that the jump height increased as the spring stiffness increased (P < 0.05). However, there was no significance difference between conditions NoExo and NoExo2. Analysis of condition Exo2S2 showed that training with the exoskeleton significantly increased than all other conditions (P < 0.0001). The average for condition Exo2S2 was 45.9±7.3 cm (meanSD), which was 2.7 cm higher than the average NoExoS2 condition, and 8.2cm (meanSE) higher than the average for condition Exo0 (i.e., an increase in height of 6.2% and 21.6%, respectively). Furthermore, we checked whether the subjects’ vertical jumping ability changed between the two experimental sessions and found no significant difference between the conditions without the exoskeleton (NoExo, NoExo2, and NoExoS2, P > 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 Appendix C.

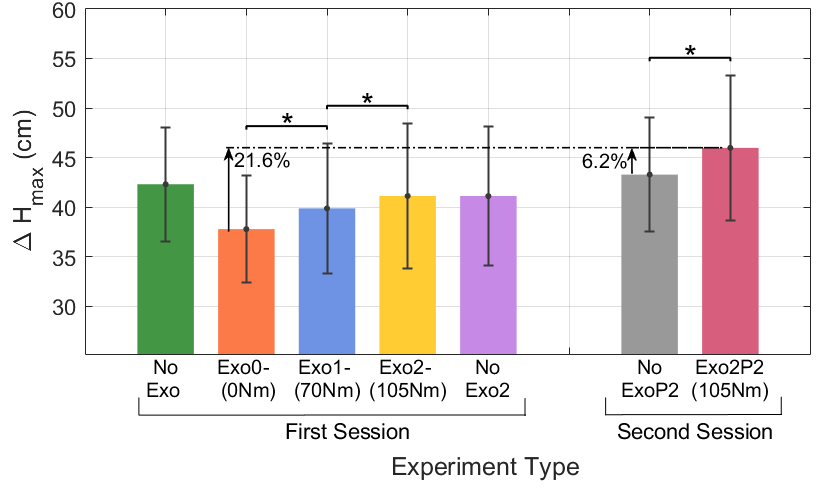


Fig. 3. Maximum jump height relative to standing for each of the seven jumping conditions. Results are averaged across subjects. Error bars are SD and

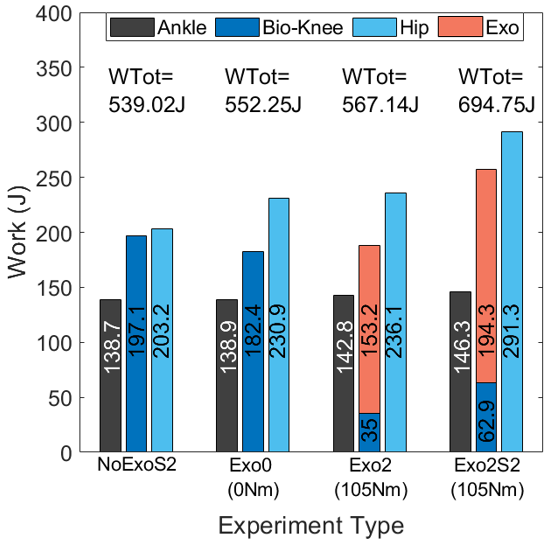
To better understand these results, we used the data from the inverse dynamics analysis for four conditions: Exo0, Exo2, NoExoS2, and Exo2S2. First, we calculated the joint work done by the ankle, knee, and hip, as given by Eq. (3), for both legs together. We also calculated the net biological knee work and net exoskeleton work )Fig. 4(. The total joints and exoskeleton work at the Exo2S2 condition was 694.7590.9 J and exceeded the work done in all other conditions (P < 0.0001). For example, it exceeded the work done in NoExoS2 and Exo0 by 155.79 and 142.59 J (meanSE), respectively. Also, the total knee work (i.e., exo+bio) for the Exo2S2 condition was greater than the work done in all other conditions (P < 0.0001). Additionally, all the conditions with the exoskeleton increased the work done by the hip relative to the work done in the NoExoS2 condition (P < 0.01). Furthermore, the hip work was the greatest in condition Exo2S2 compared to all other conditions (P < 0.0001). 

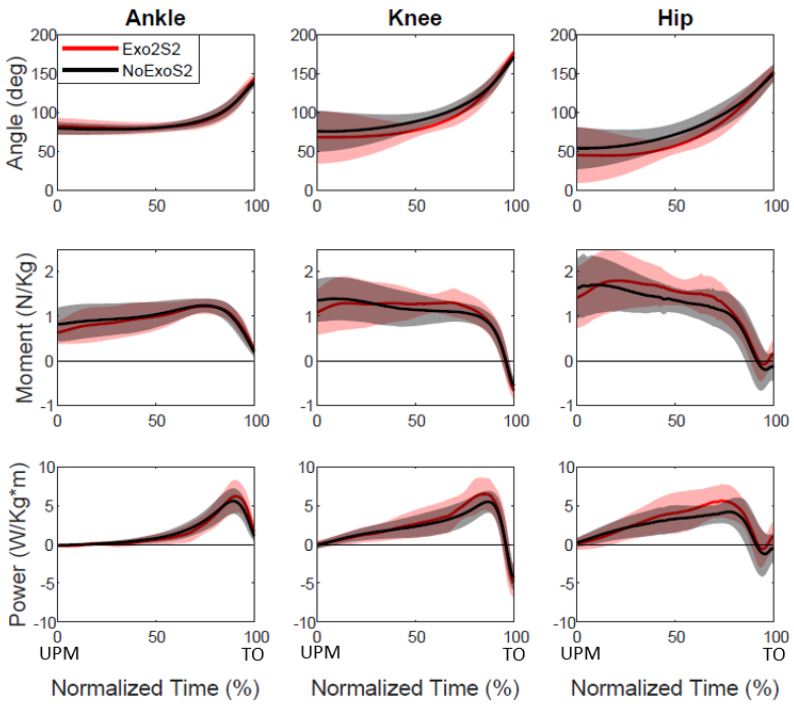
Fig. 4. Work done by exoskeleton and biological knee, ankle, and hip joints from upward movement (UPM) to take-off (TO) for conditions NoExoS2, Exo0, Exo2, and Exo2S2, both legs. The results are averaged across subjects.

Next, we compared conditions NoExoS2 and Exo2S2 based on the profiles of the angle, moment, and power at the ankle, total knee (bio+exo), and hip. We examined these parameters from upward movement (UPM) to take-off (TO) and normalized this phase of the motion to 100% so that the results from the two conditions would have the same scale (see Fig. 5). Appendix D gives all the data (not normalized) for the subject’s jumps from standing to TO. Given the symmetry, we show only data from the right leg. The comparison shows that the joint angles, moment, and power undergo similar trajectories. The peak of the average total knee moment without exoskeleton (NoExoS2) for the right leg was 1.39 N/kg, which is about 101N m. Furthermore, Table I shows quantitative information on the average joint angle at the UPM point and for conditions NoExoS2, Exo0, Exo2, and Exo2S2. At the UPM point, the angles at the knee and hip for condition Exo2S2 were smaller than for condition NoExoS2, indicating greater joint flexion (P < 0.0001). The lowest COM height (i.e., largest was for condition Exo2S2 (P < 0.0001). Also, for condition NoExoS2 was greater than for conditions Exo0 and Exo2, which means that the COM height of the former was lower than that of the latter two (P < 0.03).

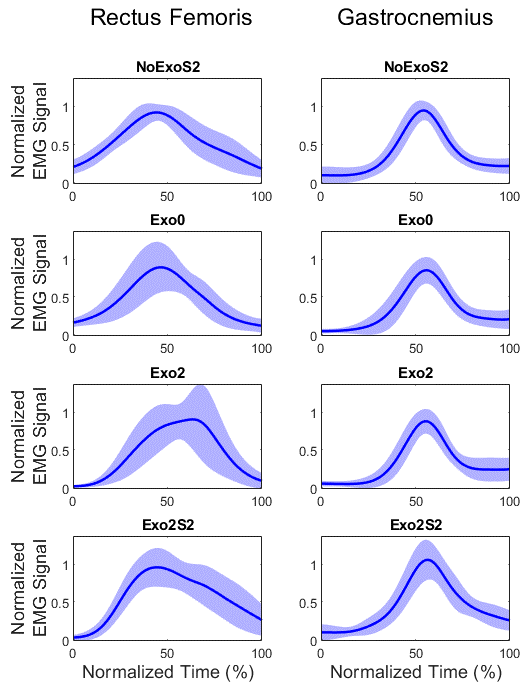
TABLE I

Average Joint Angles and Minimum COM at UPM

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | NoExoS2 | Exo0 | Exo2 | Exo2S2 |
| **Squat Angle (deg)**  Ankle  Knee  Hip | 78.0  71.1  48.9 | 79.0  74.5  47.5 | 78.8  77.4  44.9 | 80.2  59.2  35.2 |
|  |  |  |  |  |
| **(cm)** | 37.9 | 35.2 | 35.2 | 44.6 |

Fig. 5. Angle, moment, and power at ankle, hip, and total knee (bio+exo) during conditions NoExoS2 and Exo2S2, from upward movement (UPM) to take-off (TO), for right leg. The solid line gives the average over the five final jumps of all subjects for all jump conditions, and the shaded area is the SD.

Finally, Fig. 6 compares the normalized EMG signals for conditions Exo0, Exo2, NoExoS2, and Exo2S2.

Fig.6. Normalized EMG signals of rectus femoris and gastrocnemius muscles during conditions NoExoS2, Exo0, Exo2, and Exo2S2. The solid line is the average over the final five jumps of all subjects and for all jump conditions, and the shaded area is the SD.

The peak of the rectus femoris EMG signal does not statistically differ for all these jumps (P > 0.4), and the peak of the gastrocnemius EMG signal is similarly constant for all conditions except Exo2S2. The EMG signal for condition Exo2S2 was the largest of all conditions (P < 0.01) and is 12.7%% greater than for condition NoExoS2. Note that the EMG signal was examined from standing (0.25 s before UPM) to and was normalized to 100% so that the results from the four conditions are on the same scale.

# Discussion

The results show that, after training to jump with the exoskeleton, the subjects increased their jump height by 6.2% 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 [32], [33], 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 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 .

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

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where is the predicted height when using the exoskeleton, 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 is the difference between the COM height when standing and the minimum COM height (when squatting), and 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 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 46.1 cm, whereas the actual height gained is 45.9cm (meanSD). This confirms the quality of the fit to the measurements.

Next, we analyzed the energy balance to compare the predicted height with the actual height for jumping with and without the exoskeleton (i.e., conditions NoExoS2 and Exo2S2). In this case, the mass differs for the two conditions because Exo2S2 includes the exoskeleton mass. The calculation gives

(7)

where is the average mass of the human subjects, is the exoskeleton mass, and , are for Exo2S2, and and are for NoExoS2.

Accordingly, based on the experimental results for condition NoExoS2, the expected jump height for condition Exo2S2 is 53.7 cm, whereas the actual height in the experiments is 45.9cm (meanSD). Comparing the result predicted, and the actual height based on conditions Exo0 and Exo2S2 resulted in negligible differences. This difference in predicted and actual height based on NoExoS2 and Exo2S2 is significant and indicates that not all changes in joint work translate into different jump heights. The difference between the two predicted jumps heights (Exo2S2 based on Exo0 vs. Exo2S2 based NoExoS2) 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*. [1]) 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 [18]–[20] that used professional athletes weighing about 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 26% of the total knee work, which is an improvement over the first experiment, where the biological knee contributes only 17% of the total knee work.

In addition, we compare our findings with simulated human jumping with a passive exoskeleton [34], 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 9% 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 one 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 [34] 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 [35], [36].

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 (see also Appendix C).

According to multiple studies, countermovement jumps are almost always higher than squat jumps [18], [37]–[39]. Komi *et al*. [38] 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 [37], [40]–[42] since significantly more energy is lost as heat during a countermovement jump than during a squat jump. Bobbert *et al*. [37] 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.

# Conclusion

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

The study discusses two experimental sessions. In the first session, the subjects were equipped with the exoskeleton and jumped without the benefit of instructions on how to use it. In the second session, the subjects 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 6.2%0.9% (meanSE) when using the exoskeleton compared with the jump height without the exoskeleton, and an increase in jump height of 21.6% compared with jumping with a springless exoskeleton.

The lack of improvement in jump height during the first session indicates that exploration is necessary to increase the jump height.

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 additional jumping techniques, including countermovement.

## Appendixes

Appendix A:

Contributions to Passive Exoskeleton Mass by Component for One Leg

|  |  |
| --- | --- |
| Segment | Mass |
| **Aluminum frame** | **1272 g** |
| Net spring  Spring with attachments | 14.8 g  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.

Appendix B: Calculation of the exoskeleton work

The design of the knee exoskeleton required using a lightweight spring with a suitable spring constant, which took the form of a rubber tubing generally used for spear guns. However, because rubber materials exhibit viscous behavior, the force-length curve depends on the stretching velocity. Our initial intent was to use an s-type sensor to measure the forces. However, due to the dimensions of the exoskeleton, the s-type sensor could only be used with a single spring attached to the exoskeleton. Thus, we developed a model to determine the spring force based on experimental data.

Several models are available to describe viscoelastic materials, all of which combine springs and dampers (Fig. B1).

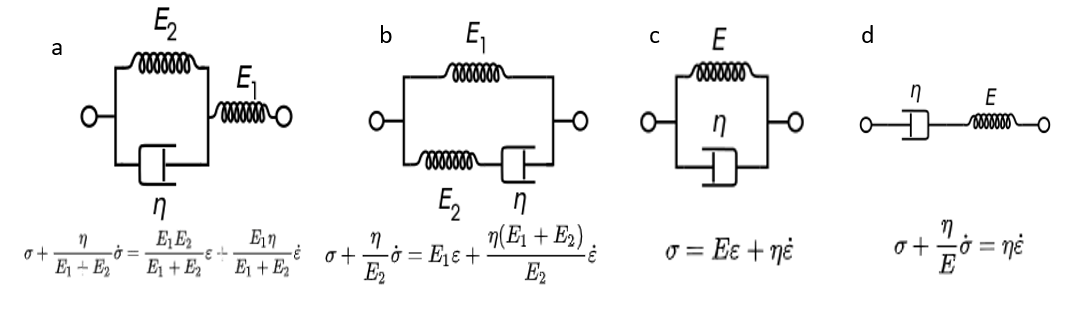
We experimented to find the most suitable model for our spring. In the experiments, two subjects jumped 20 times (six squat jumps, six countermovement jumps, and eight continuous jumps). The force was measured at 125 Hz by using an S-type instrument (model 363, Vishay, Malvern, PA, USA) with an A-to-D board (PhidgetBridge 4 Model 1046\_0B, PHIDGETS Inc., Calgary, Canada). Next, we developed a Mathcad program to optimize the model parameters for each of the four models (i.e., we minimized the least-squares error between the model and the experimental data). The Kelvin–Voigt model provided the best fit with a minimum of parameters. Thus, our model is

Fig. B1. Four viscoelastic models: (a) Kelvin representation, (b) standard linear solid model Maxwell representation, (c) Kelvin–Voigt model, (d) Maxwell model, where E is the Young’s modulus and η is the damping coefficient.

(1)

where is stress, is the Young’s module, η is the damping coefficient, is the strain, and is the strain rate.

To convert stress into force, we used

(2)

where *A* is the true cross-sectional area of the rubber spring and is the initial force due to the initial tension of the spring.

Combining (1) and (2) gives

(3)

where is the initial volume of the spring, *L* is the spring length, which depends on the angle, and are computed from the knee angle and angular velocity.

The strain , where *R* is the radius of the exoskeleton pulley (Fig. B1), is the initial spring length, and is the change in the knee angle. Thus,

(4)

Next, we insert the radius (55 mm), the initial length of the spring (50 mm), and the initial radius of the spring (9 mm) to obtain

In our trial experiments, we measured .

To find , we applied a least-squares fit using Matlab and obtained with a correlation factor . Another measure of the accuracy is the difference in the work calculated for each jump. The mean error in the work for each simulated moment relative to experiment is 4.6% with standard deviation of 13%.

Upon examining the data, we noticed an interaction between the effect of strain and the effect of strain rate. Thus, by using a curve fit, we add to the Kelvin model a component Cϵ, obtaining

(5)

which gives with a correlation factor *R*2 = 0.93, a mean work error of 2.4%, and a standard deviation of 13.3%. Fig. B2 shows the model results vs the experimental results for a sample of nine jumps.

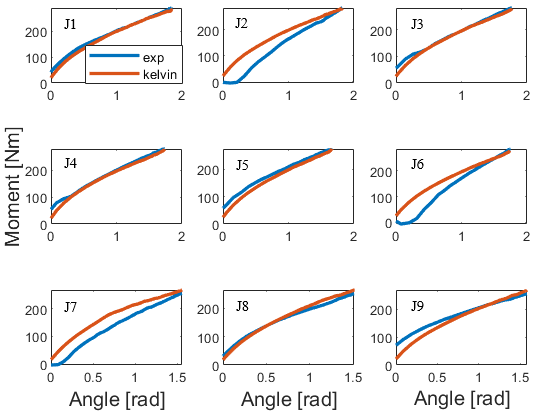


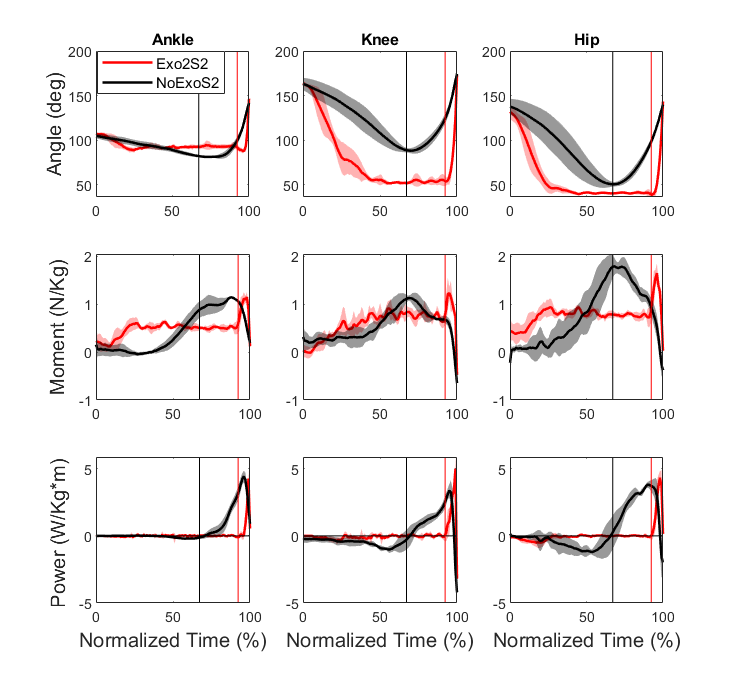
Fig. B2. Nine jump examples showing the fit of the force prediction (red curves) vs the experimental result (blue curves).

To calculate the total work, we use

(4)



Appendix C: for each subject for conditions NoExoS2 and Exo2S2.



Appendix D: Angle, moment, and power of ankle, total knee (exo+bio), and hip from standing to take-off (TO), of one subject (AverageSD of five jumps), right leg. The vertical lines represent the start of upward movement (UPM) for each jumping condition. For condition Exo2S2, the subject reaches a squat position and searches for the right position for several seconds until the start of upward movement. Thus, his jumping strategy with the exoskeleton is more like a squat jump as opposed to a countermovement without the exoskeleton. Note that the normalized time is calculated differently than in Fig. 5.

Acknowledgment

The authors would like to thank Professor Yisrael Parmet for his advice regarding the proper statistical methods, 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 to predict the spring forces.

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1. This paper was submitted for review at XXX. This work was supported in part by the Helmsley Charitable Trust through the Agricultural, Biological and Cognitive Robotics Initiative of Ben-Gurion University of the Negev and the Israel Science Foundation under Grant 899/18.

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