Passive Knee Exoskeleton Increases Vertical Jump Height

Coral Ben-David, Barak Ostraich, and Raziel Riemer

***Abstract*—Most exoskeletons are designed to reduce the metabolic costs of performing aerobic tasks such as walking, running, and hopping. This study presents an exoskeleton that boosts vertical jumping—a fast, short movement during which the muscles are exerted at peak capacity. It was hypothesized that a passive exoskeleton would increase vertical jump height without requiring external energy input. The device comprises springs that work in parallel with the muscles of the quadriceps femoris. The springs store mechanical energy during knee flexion (the negative work phase) and release that energy during the subsequent knee extension (the positive work phase), augmenting the muscles. Ten healthy participants were evaluated in two experimental sessions. In the first session, the participants jumped without receiving instructions on how to use the exoskeleton, and the results showed no difference in jump height when jumping with the exoskeleton or jumping without it. In the second session, the participants were instructed to achieve deeper initial squat heights at the start of the jump. This resulted in a 6.4% increase in average jump height compared to jumping without the exoskeleton (each participant performed five jumps for each the two conditions). This is the first time that a passive exoskeleton has been shown to improve the height of a vertical jump from a dead stop.**

***Index Terms*—Adaptation, augmentation, exoskeleton, vertical jumping.**

I. Introduction

EXOSKELETONS are used primarily for physical rehabilitation or the augmentation of human physical performance. Such performance enhancement is desirable across a variety of activities, and there are potential exoskeleton applications for both athletes and workers in physically demanding environments (e.g., industrial workers, police officers, soldiers, firefighters). Most wearable exoskeletons studied in previous research were designed to enhance aerobic activities by reducing metabolic cost. Over the past decade, some studies have demonstrated that the use of exoskeletons can indeed reduce the metabolic power required for repetitive activities such as walking [1]–[5], running [6]–[8], and hopping [9], [10]. Humans also perform fast, short motions (duration of les then 1 s) in many ways (e.g., jumping, throwing). Since these are anaerobic activities, muscle activation for them is very different, yet only a few studies have looked at the augmentation of humans for such activities. Further, we are unaware of any studies on developing exoskeletons that can successfully enhance a single discreet vertical jump. In contrast, there are devices such as spring-based jumping shoes, pogo sticks, and trampolines that increase jump height by accumulating energy over the course of several jumping cycles. When designing an exoskeleton that would successfully aid vertical jumping, it is imperative to first understand the work involved in the action. A vertical jump begins with a negative work phase that involves flexion of the hips, knees, and ankles (dorsiflexion). In this phase, the jumper briefly lowers his/her body into a squatting position. Subsequently, a positive work phase commences with sequential extension of the hip, knee, and ankle (plantarflexion). This phase begins at the start of the upward movement—as the jumper pushes his/her body out of the squatting position—and ends as the toes leave the ground [11]. To enable the flight phase, the energy produced during the motion from the lowest squat position through to takeoff (i.e., positive work) must exceed the energy required to lift the jumper's center of mass (CoM) from the lowest squat position to standing height (Fig. 1a). During the positive work phase of a jump, the muscles working at the hips, knees, and ankles produce high moments of approximately 200–350 N·m for the two legs combined [11]–[13]. The muscles produce mechanical power acting at each leg joint in the range of 1000–2500 W, with a peak angular velocity of approximately 15 rad/s [13]–[15].

Several approaches can be taken to design an exoskeleton for jumping. The first is an active exoskeleton with actuators (i.e., motors, hydraulics, and/or pneumatics) that add energy to the leg joints. Such exoskeletons have been used to aid walking and running [16], [17]; they allow the applied moment–time profile to be specified and provide additional power at the joint level, which affects the muscle–tendon structure during the motion from the lowest squat position through to takeoff (i.e., the positive work phase; Fig. 1b). These active exoskeletons

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This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the IRB Ben-Gurion University of the Negev under Approval No. 12345, Dated: 11 June 2019.

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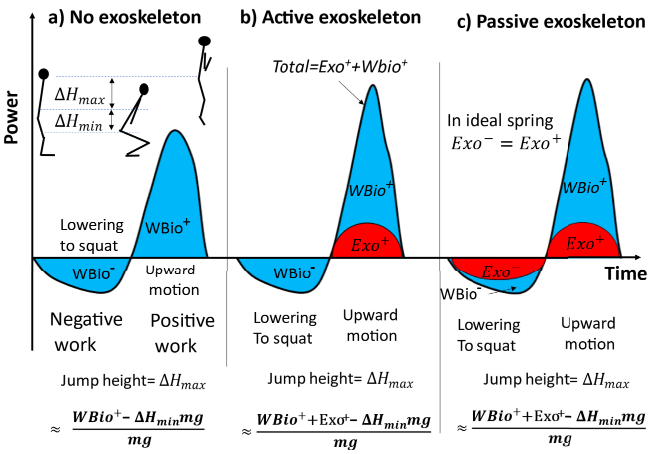

Fig. 1. Conceptual examples of energy exchange and jump height. (a) When jumping with no exoskeleton, the jump height (ΔH_{max}) is defined as the difference between the maximum height of the center of mass and its location while standing. This is a function of the positive work performed during the upward motion minus the energy required to lift the center of mass from the squat position to a standing position (ΔH_{min}). (b) Assuming the squat depth to be the same height both with an exoskeleton and with no exoskeleton, the addition of the positive work provided by the exoskeleton (Exo^+) to the muscles ($WBio^+$) increases the total positive work (black line), resulting in a higher jump. (c) In a passive exoskeleton, the stored energy (Exo^-) comes from the work against gravity and from the muscles contracting against the springs; subsequently, during the positive work phase, this energy (ignoring loss due to the mechanical characteristics of non-ideal springs) supplements the muscle work to increase the jump height. Note that these calculations ignore loss of energy due to soft tissue [23] and internal work performed on the body segments.

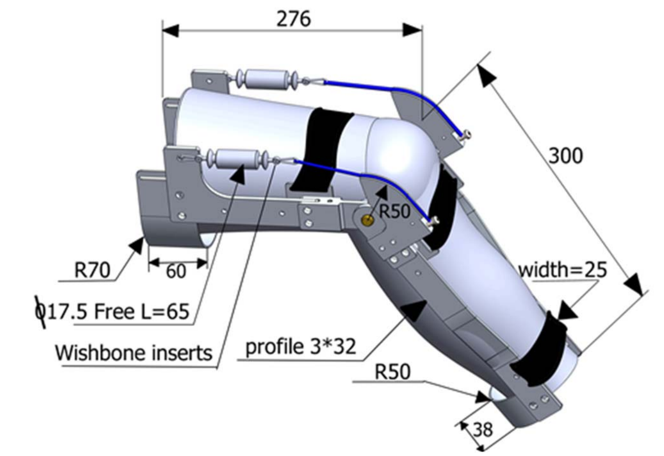

Fig. 2. The designed knee exoskeleton. The exoskeleton comprises aluminum frames (attached to the leg with wide Velcro straps) and rubber springs acting parallel to the quadriceps femoris muscle.

incorporate motors, gears, and power supplies, which might make the devices heavier. Two previous studies used this approach to enhance vertical jumping. The first designed an ankle device with motors placed in a backpack (3.95 kg). The motors provided actuation—via hydraulic lines—to the ankle device (0.9 kg on each shank), with a total device weight of 6.2 kg. The study reported that users could jump using the device, but not if they improve their jump height [18]. The second study tested a hip-based device with motors placed on the torso (total device weight of 6 kg). The study began with six subjects and an experiment in which the device delivered 20 N·m to each hip. Then, only the three subjects who had satisfactory results in the first experiment proceeded to a second session involving greater hip assistance. These three subjects achieved an average improvement of 8% [19]. Second approach is active exoskeleton that utilizes a small motor, which stretches a spring that stores mechanical energy until the moment of the jump, similar to the mechanics of a grasshopper's hop [20]. However, there has been no research to test this approach. One possible drawback of this type of device is the relatively long preparation time for the jump. A third approach centers on a passive exoskeleton with springs [7], [8], whereby the spring is stretched (converting work to potential energy) during a phase of the jump motion sequence in which the joints perform negative work and then returns this energy in the phase of motion during which the joints perform positive work [21]. Kim *et al* [22] built and tested a passive-elastic ankle exoskeleton to enhance vertical jumping. During pilot tests, the participants nearly reached their peak vertical jump height with the exoskeleton but could not surpass it.

While each approach has its advantages and disadvantages, passive exoskeletons are typically cheaper and lighter than active exoskeletons. In choosing to develop a passive device, we hypothesized that such a device could increase vertical jump height without adding external energy to the human–exoskeleton system. This is achieved because during the lowering motion sequence, the springs are stretched. Next, the stored energy in the spring supplements the work performed by the muscle–tendon structure in the jumper's knee during the positive work phase, thus increasing the total positive knee-joint work output (Fig. 1c).

The goals of our study were: 1) to test whether a passive exoskeleton can indeed improve vertical jump height, 2) to better understand how to develop exoskeletons for such movement, and 3) to examine human–exoskeleton interaction. While both the knee and hip are good candidates, this study built and experimentally tested a passive knee exoskeleton equipped with springs working in parallel with the muscles of the quadriceps femoris. The springs store energy during the negative work phase and release that energy during the subsequent positive work phase. We focused on the knee joint because of the large moments involved in movements of this joint and because the knee behaves as a one-degree-of-freedom joint, which makes for a simpler device design than would be required for the hip joint.

II. Methods

A. Exoskeleton Design

We designed and constructed a pair of passive knee exoskeletons (Fig. 2). Each exoskeleton comprised frames of 6061 aluminum alloy attached to the leg with wide Velcro® straps. There was polyurethane foam (10 cm wide and 5 mm thick)—the type used for cushioning in orthopedic and prosthetic devices—between the metal arches at the back of the leg. Rubber springs typically used in spearguns (Sigal Reactive Evo Brown Coextruded Tires, SIGALSUB, Romano Canavese, TO, Italy) were aligned parallel to the muscles of the quadriceps femoris (to contribute to the knee moment).

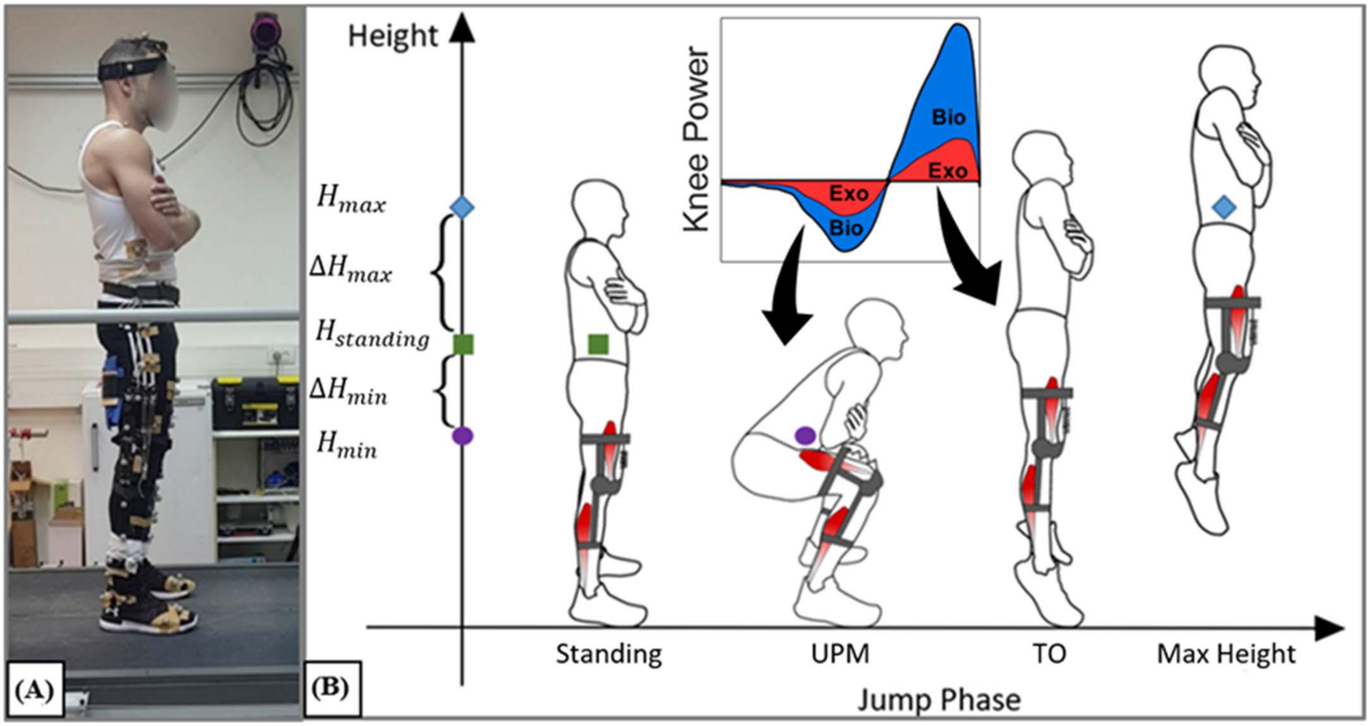

Fig. 3. The jump experiments. (a) A participant wearing the exoskeleton for vertical jumping. He is standing on an instrumented treadmill with each leg on a different force plate and anatomical markers affixed to his body. (b) The different phases of the vertical jump: Standing in the starting position for the upward movement (UPM), followed by takeoff (TO) and reaching maximal height. During knee flexion, the springs are stretched, and then, from UPM to TO, the stored energy in the springs is added to the mechanical energy produced by the muscles. The CoM height parameters are also presented according to the phases of the jump. The muscles in red represent the knee extensor muscles and the ankle extensors (plantar flexors).

The springs were connected using wishbone inserts. The exoskeleton was designed with a mechanical stop to prevent hyperextension of the knee joint, which could be damaging. The total mass of each exoskeleton was about 1.5 kg, with the mass of the springs being approximately 72 g. The masses of the exoskeleton components are presented in Supplementary Table SI.

B. 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 and completed both sessions. Because just one pair of exoskeletons was available, only participants on whom the exoskeleton fitted were selected. The initial sample size was 12, but two participants dropped out during the experiments: one was afraid of using the exoskeleton and consequently executed jumps almost without bending his knees; the other experienced knee pain while jumping with the exoskeleton because it was too narrow at his knees. All participants provided written informed consent before participating in the study. The study was approved by Ben-Gurion University's Human Research Institutional Review Board.

C. Protocol

The effects of the exoskeleton boost were compared across various conditions in two experimental sessions. In the first of these, the participants jumped as high as possible, without instructions on how to use the exoskeleton to assist their jumps. The COVID-19 lockdown halted the experiments at this point. However, during the lockdown, we used a computer simulation [23] to explore how the participants might improve their jumps using the exoskeleton and found that they needed to bend their knees further than they had in the first session. When COVID-19 restrictions were lifted temporarily (about three months after the first session), we conducted a second experimental session. In both sessions, the participants performed a warm-up routine: walking on a treadmill at 1.6 ms^{-1} for 4 min, followed by free jumping. Then, for each jump, they were instructed to jump as high as possible with their hands crossed over their chests (Fig. 3). To prevent fatigue, the participants rested for 2 min between jumps. The phases of the jump are illustrated in Fig. 3. During the first session, the participants jumped vertically under five different conditions: without the exoskeleton (NoExo1); with the exoskeleton but with no springs connected (i.e., the exoskeleton as a deadweight; Exo0); with the exoskeleton with two springs attached, delivering a total of 70 N·m (total of both knee exoskeletons) at a 90° knee bend (Exo70); with the exoskeleton with three springs attached, providing a total (both exoskeletons) of 105 N·m at a 90° knee bend (Exo105S1); and, once again, without the exoskeleton (NoExo2). The three different exoskeleton conditions were conducted in random order, but the experimental session always began with NoExo1 and ended with NoExo2 as control conditions. The participants then jumped vertically eight times under each condition, and the data were collected from the final five jumps.

The nominal moments provided by the exoskeleton were based on tensile tests of the rubber springs that relate spring force to strain ratio. The tests were conducted with a universal testing machine (Hounsfield, H10KT). The 70 N·m and 105 N·m moments were equivalent to spring stiffnesses of 38 N·m/rad and 57 N·m/rad, respectively, which reflects a compromise between providing larger moments and keeping the device compact and lightweight using relatively affordable components. Based on previous studies [11]–[13] with professional athletes, these values delivered approximately 20% and 33% peak knee moment, respectively, during the jumps.

The second session aimed to test if the participants could learn how to better utilize the exoskeleton. Because the results of the first session revealed a positive correlation between spring stiffness and jump height, the second session included only two conditions: one without the exoskeleton (NoExoS2) and one with the exoskeleton with springs delivering 105 N·m at a 90° knee bend, with a practice jump session before the recorded jumps (Exo105S2). In both conditions, the participants warmed up as they did in Session 1. Then, for the *no exoskeleton* condition, they performed three warmed up on the treadmill and five, maximum effort jumps like in session 1 (see Supplementary Fig. S1 for a summary of both sessions). To encourage adaptation to the exoskeleton in the second session, we directed the participants to explore lower squat positions. The experimental protocol was inspired by two studies: one by Gast *et al.* [24], which found that walking on rough terrain while exploring various walking speeds reduced the time for the convergence of the cost of transport to a minimum while walking at the preferred speed, and the other by Selinger *et al.* [25], who found that participants who walked with exoskeletons discovered their optimal step frequency only after exploratory sessions during which they walked at high and low step frequencies. To train the subjects to better utilize the exoskeleton, they executed four squat jumps with different starting postures with varying depth of squat. They were given minimal instructions regarding possible ways to achieve the postures (e.g., "bend more at the knees"). We then chose the jump with the highest vertical height and tweaked the technique (e.g., slightly more or less flexion at the hips or knees) to optimize the results. The participants were instructed to keep their feet a pelvic width apart to the fullest extent possible. Each participant executed up to 10 training jumps to adapt to the new jumping starting posture with the exoskeleton. Then they performed five maximum-effort jumps.

D. Data Collection

The motion of the participants was recorded using 14 cameras operating at 179 Hz (Qualisys, Gothenburg, Sweden) and tracking 48 reflective markers affixed to each participant. The location of the markers relative to the human body was based on studies by Ferrari *et al.* [26], Leardini *et al.* [27], and Seay *et al.* [28]. In addition, when using the exoskeleton, eight markers were placed on each exoskeleton (Supplementary Fig. S2). In the exoskeleton condition, the knee markers had to be removed (they were replaced with markers on the exoskeleton), and the leg marker cluster had to be moved slightly to facilitate donning the exoskeleton, bringing the total number of markers to 60. The ground reaction forces for each leg were recorded at 2040 Hz using an instrumented treadmill (Bertec, Columbus, OH, USA). Kinematic and ground reaction force data were filtered using fourth-order Butterworth low-pass filters with 10 Hz and 35 Hz cutoff frequencies, respectively. One jump of one participant was omitted due to a force plate initialization malfunction. The activity of the right-leg rectus femoris muscle was measured using surface electromyography (EMG) sensors (Trigno Wireless System, Delsys, Boston, MA, USA) at 2000 Hz. We chose to examine this muscle because of its contribution to knee extension moment. The skin around the attachment of the EMG sensors, which used adhesive tape provided by the manufacturer, was shaved and scrubbed clean with 70% alcohol. However, due to sweating and shock during landings, the EMG sensor on the rectus femoris muscle moved for three participants during the final tests. The data from those jumps were not used. 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. The EMG data were rectified and filtered using a second-order low-pass Butterworth filter with 3 Hz cutoff frequency. This signal processing was based on [29], [30].

E. Data Analysis

The data from all measuring 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 [31] and a six-degree-of-freedom method to calculate joint angles, angular velocities, body CoM, moments, and power in the sagittal plane)because jumping almost entirely involves sagittal plane motion(. Segment mass was estimated based on the study by Dempster [32], and the location of the CoM and moment of inertia were estimated based on the study by Hanavan [33]. For the exoskeleton conditions, the masses of the upper and lower parts of the exoskeleton were distributed between the thigh and shank (affecting both the mass and moment of inertia of the segment). The height of the CoM was calculated using data from the markers, which is considered the standard for evaluating vertical jump performance [34]–[42].

The angles of 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 it increases during plantarflexion. The knee angle is measured from the shank to the thigh; when standing, it is about 180°, and it decreases during flexion. Finally, the hip angle is measured from the thigh to the pelvis; when standing, it is about 180°, and it decreases during flexion.

MATLAB was used to calculate the CoM height, kinetics, and kinematic parameters. ΔH_{max} (or ΔH_{min}) is defined as the difference between the standing CoM and the maximum (or minimum) height of the CoM (Fig. 3). Specifically,

$$\Delta H_{\max} = H_{\max} - H_{\text{standing}} \tag{1}$$

$$\Delta H_{\min} = H_{\text{standing}} - H_{\min} \tag{2}$$

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 point of the upward movement (UPM) to takeoff (TO; note this is also the lowest point that the CoM would reach during the jump). Specifically,

$$W_j = \int_{UPM}^{TO} P_j dt = \int_{UPM}^{TO} M_j \omega_j dt \quad (3)$$

where P_j is the power at joint j, M_j is the flexion-extension moment at joint j, and ω_j is the angular velocity at joint j. The UPM point is determined at the minimum CoM (H_{min}), with the CoM rising from this point onward. The TO is determined as the instant when the ground reaction force initially reaches zero. The total knee power and work have contributions from both the exoskeleton and biological exertions. The exoskeleton power was calculated using a model that predicts the moment provided by the exoskeleton—based on experimental data—and multiplies that value by the measured angular velocity (see Supplementary Materials for model of exoskeleton):

$$W_{Exo} = \int_{UPM}^{TO} P_{Exo} dt = \int_{UPM}^{TO} M_{Exo} \omega_{knee} dt \quad (4)$$

The biological knee work, which is obtained by subtracting the work done by the exoskeleton from the total work done by the knee, is given by

$$W_{BioKnee} = W_{totaltKnee} - W_{Exo}. \quad (5)$$

Further, (3), (4), and (5) were used to calculate the joints' work during the downward motion from standing to UPM.

F. Statistics

For each participant, there were five jumps for each of the conditions. A linear mixed model (LMM), with the participants as a random effect across all jumping conditions (i.e., NoExo1, Exo0, Exo70, Exo105S1, NoExo2, NoExoS2, and Exo105S2) was used to examine how the exoskeleton affected average jump height. The random effect was due to variations in participants' physical traits (e.g., height, mass, muscle fiber composition) and jumping techniques (e.g., differences in the degree of bending at the knees). LMM analysis of the following parameters was also conducted: 1) work performed by the joints and the exoskeleton, 2) joint angles, 3) ΔH_{min}, and 4) ΔH_{max}. In addition, Q–Q plots were used to ensure that the residuals of the models were normally distributed. Post-hoc pairwise comparisons were conducted using Tukey's honestly significant difference test, with a significance level of 0.05. Statistical analysis was performed using R-studio, Ver 1.1.463 (R Ver 3.5.1; RStudio, Inc. Boston, MA, USA).

III. Results

A. Jump Height

Jump height is defined as the difference between the height of the jumper's CoM while standing upright and the maximum jump height (ΔH_{max}).

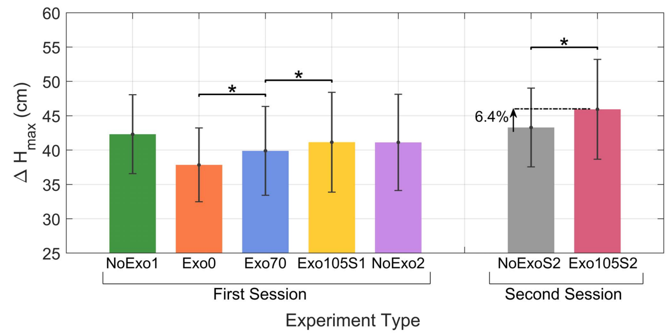

Fig. 4. Maximum jump height relative to standing. The maximum jump height for each of the seven jumping conditions. Results are averaged across participants. Error bars are 1 S.D.; * $P \leq 0.05$ (10 participants, five jumps for each condition).

In the first experimental session, the ΔH_{max} for conditions Exo0, Exo70, and Exo105S1 increased in tandem with increases in the spring stiffness. Ten participants each performed five jumps at each stiffness value, providing a total of 50 data points for each condition ($P < 0.05$; paired Tukey's and HSD; Fig. 4). In the first session, ΔH_{max} differed marginally, but not significantly, between the NoExo1 and NoExo2 conditions [0.42 ± 0.057 m (± SD) vs. 0.41 ± 0.069 m; $P = 0.06$]. In the second session, the Exo105S2 condition achieved ΔH_{max}, which was significantly higher than in all the other conditions from both sessions ($P < 0.0001$). The mean ΔH_{max} for the Exo105S2 condition was 0.459 ± 0.073 m (±SD), which was 0.027 ± 0.032 m higher than for the NoExoS2 condition (i.e., an increase in height of 6.4% (a. Furthermore, when checking whether the vertical jumping ability of the participants under the NoExo conditions had changed between Session 1 and Session 2, no significant difference was found ($P = 0.2$). During the second session, seven of the 10 participants jumped higher with the exoskeleton (Exo105S2) than without it (NoExoS2). Supplementary Fig. S5 presents a comparison on each subject.

B. Joint and Exoskeleton Work

To better understand the jump height results, an analysis of four of the conditions was performed: Exo0 and Exo105S1 from Session 1 and NoExoS2 and Exo105S2 from Session 2. First, the work performed at the ankle, knee, and hip joints from the start of UPM to TO was calculated, with the calculation performed separately for each leg and then summed. Another calculation was made for the net muscle–tendon work at the knee and for the net exoskeleton work (Fig. 5, Table SII). The total joint work, including exoskeleton work, under the Exo105S2 condition (Session 2) was 680.6 ± 90.8 J and exceeded the work performed under all the other conditions ($P < 0.0001$; paired Tukey's and HSD). The total knee work (i.e., exoskeleton work + muscle–tendon work) for the Exo105S2 condition (Session 2) exceeded the work performed under all the other conditions ($P < 0.0001$). Furthermore, in all the exoskeleton conditions with springs, the work performed at the hip increased relative to jumping without the exoskeleton, which is referred to as *no exoskeleton* (NoExoS2) condition ($P < 0.05$), but the difference in this parameter for NoExoS2

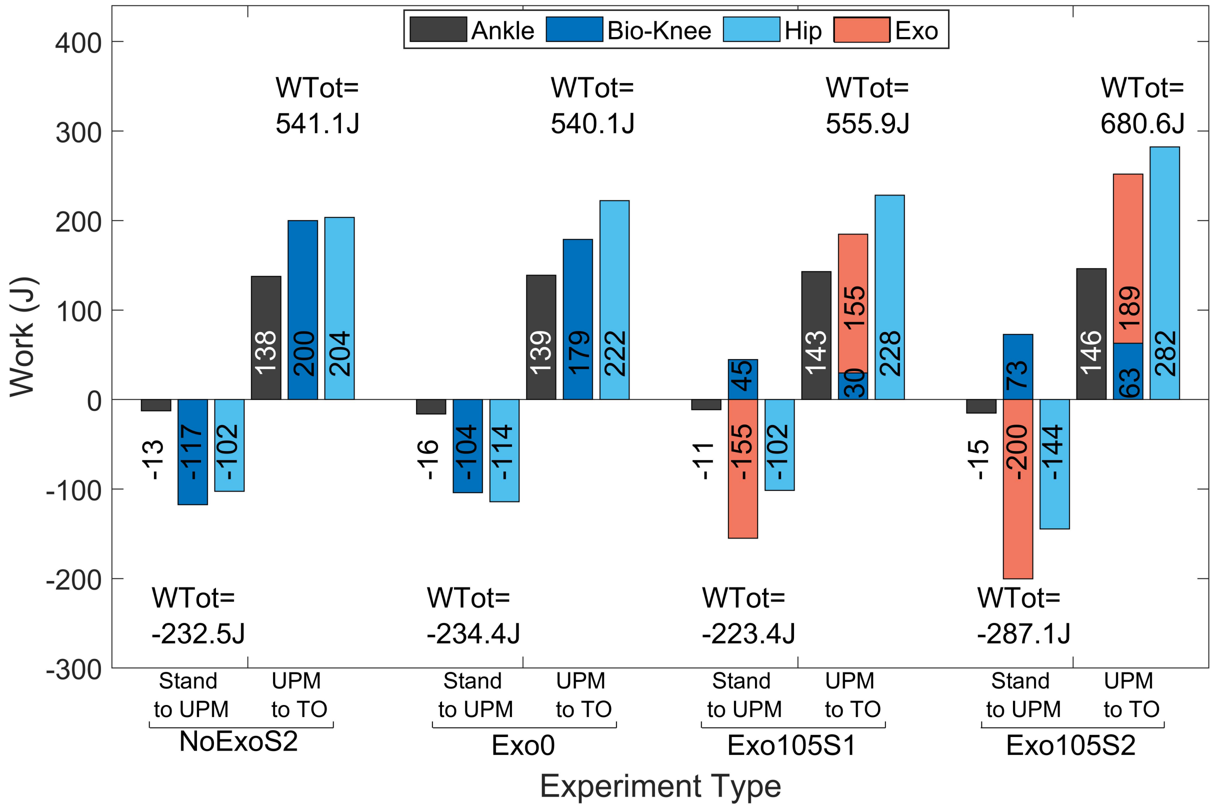

Fig. 5. Work performed by the exoskeleton and joints. The work performed by the exoskeleton and the muscle–tendons at the knee, ankle, and hip joints from upward movement (UPM) to takeoff (TO) for the NoExoS2, Exo0, Exo105S1, and Exo105S2 conditions. The work presented is for the two legs combined and is averaged across participants (data for the figure can be found in Table SII).

and Exo0 was marginally significant (P = 0.08). The hip work was highest under the Exo105S2 condition (Session 2) when compared to all the other conditions ($P < 0.0001$). Under the Exo2 and Exo105S2 conditions, during the movement from standing to squatting, the total negative work at the knee was 110.46 ± 31 J and 127.47 ± 32 J, respectively, and the total energy stored in the exoskeleton spring was 155.01 ± 31.08 J and 200.27 ± 22.01 J, respectively, indicating that the muscles performed net positive work of 44.55 ± 27.74 J and 72.80 ± 29.46 J, respectively, while contracting against the springs.

C. Joint Angle, Moment, Power, CoM, and EMG

To gain a deeper understanding of the jumping techniques, we further examined conditions from the second session (NoExoS2 and Exo105S2), comparing the angle, moment, and power time series profiles at the ankle, total knee (muscle–tendon + exoskeleton), and hip during the work phase (i.e., from the UPM to TO). The duration of this phase of the motion was normalized to 100% so that the results from the two conditions could be compared on the same scale. Further, the moment and power were normalized to each participant's mass and height. (Fig. 6). Example data on one participant's jumps from standing to TO, with and without an exoskeleton, are detailed in Supplementary Fig. S6. While the work and power were calculated by summing the data for the two legs, only data on the right leg have been presented. The results for the two legs were almost identical, with the joint angles, moments, and powers having similar trajectories.

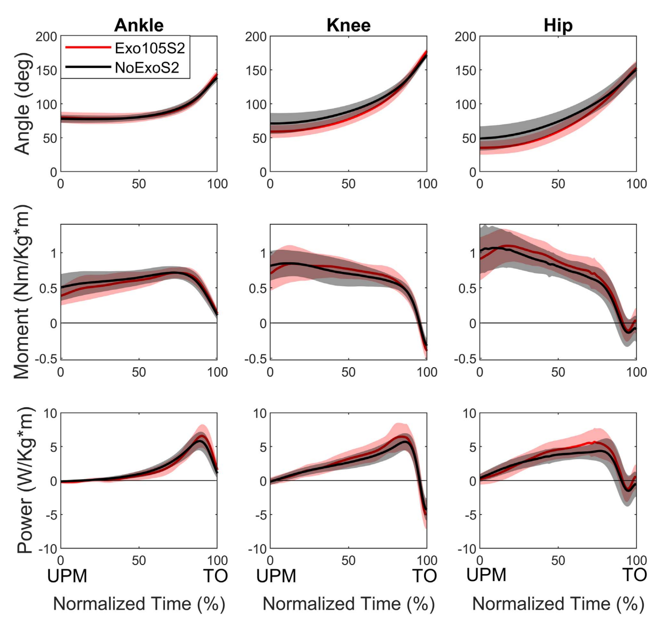

Fig. 6. Angle, moment, and power results for Session 2. The angle, moment, and power profiles of the ankle, total knee (muscle–tendon + exoskeleton), and hip during the NoExoS2 and Exo105S2 conditions, from upward movement (UPM) to takeoff (TO), for the right leg. The solid line depicts the average of the five final jumps of all participants for all jump conditions, and the shaded area is the S.D. The moment and power are normalized to each participant's mass and height.

At the UPM point, the angles at the knee and hip for the Exo105S2 condition were smaller than those for the NoExoS2 condition, indicating greater joint flexion ($P < 0.0001$; paired

TABLE I
JOINT ANGLES, MINIMUM CoM AT UPM, AND MAXIMUM HEIGHT OF CoM FROM STANDING

	NoExoS2	Exo0	Exo105S1	Exo105S2
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
ΔH_{min} (cm)	37.9 ± 8.2	33.7 ± 7.9	34.0 ± 7.4	43.5 ± 4.3
ΔH_{max} (cm)	43.3 ± 5.7	37.8 ± 5.4	41.1 ± 7.3	45.9 ± 6.1

Exo0 and Exo105S1 are conditions from the first session, while NoExoS2 and Exo105S2 are conditions from the second session.

Tukey's and HSD). The lowest CoM height reached during the negative work phase (i.e., the largest ΔH_{min}) occurred under the Exo105S2 condition ($P < 0.0001$; paired Tukey's and HSD). In addition, ΔH_{min} was larger for NoExoS2 than under the Exo0 and Exo105S1 conditions; i.e., the lowest minimum CoM height was recorded under NoExoS2 ($P < 0.001$; paired Tukey's and HSD). Table I presents quantitative information on the average joint angle at the UPM point and ΔH_{min} for the NoExoS2, Exo0, Exo105S1, and Exo105S2 conditions. EMG signals for the Exo0, Exo2, NoExoS2, and Exo2S2 conditions were normalized by dividing the signal of each jump by the average maximum muscle activity of the control conditions (i.e., NoExo for the first session and NoExoS2 for the second session). The peaks of the normalized rectus femoris EMG signals were not statistically different for all these jump conditions ($n = 50$; $P > 0.4$; Tukey's with HSD), Supplementary Fig. S7 comparison of EMG from session 2.

IV. DISCUSSION

To the best of our knowledge, this is the first study to demonstrate that a passive exoskeleton can augment jumping movement. The results show that a deeper squat engaged the utility of the exoskeleton and enhanced jump height by 6.4% compared to jumping without the exoskeleton.

A. Effect of the Dipper Squat

It may be assumed this improvement in jump height can be explained by the deeper squatting position. However, previous studies conducted without an exoskeleton found that a deeper squatting position does not affect jump height [37], [43]–[45]. Further, in this study, different squatting depths in the *no exoskeleton* condition (during both the first and second sessions) resulted in small changes in jump height, with a deeper squat recorded under NoExo2 in Session 1 ($\Delta H_{min} = 41.3$ cm) than under NoExo1 (36.5 cm) in Session 1 and NoExoS2 (37.9 cm) in Session 2. However, despite using a deeper squat under NoExo2, the jump height was the lowest of the three conditions: NoExo2 (41.1 cm), NoExo1 (42.3 cm), and NoExoS2 (43.3 cm).

In this study under the ExoS2 condition, the participants increased their knee flexion to achieve a deeper squat, which resulted in more energy being stored in the springs. This came from both gravitational force and the positive work (72.80 ± 29.46 J) performed by the knee flexor to coil the springs during the downward movement. Next, when performing the upward movement, the energy stored in the springs was released, augmenting the muscles and increasing the total knee joint moment. Thus, under condition Exo105S2, the total work performed at the knee joint exceeded that produced by the knee musculature without the exoskeleton by 28%. This was achieved despite the decrease in the work produced by the biological knee during the upward motion being 68% less than under the *no exoskeleton* (NoExoS2) condition. This might be due to changes in the muscle length and velocity.

B. Why Did the Participants Increase Their Torso Angle?

Examining the conditions with the exoskeleton revealed that the hip angle was flexed to a greater extent at the start of the UPM, which also corresponded to a lower CoM. However, it is unclear whether this additional work at the hip produced any benefit to the jump height. This is informed by a simulation study modeling a human jumping with a passive knee exoskeleton that delivered 105 N·m in total to both knees [23]. From the results of the simulation, jumping with the exoskeleton increased the jump height by 19% when compared to the *no exoskeleton* condition. There was a small difference in the total hip work: a decrease of 5%. There was an increase of 55% in the total knee work, and ankle work increased by 7%. Examining the joint angles in the simulation revealed an increase in knee flexion, while the torso remained in a relatively upright position, in contrast to experiments whereby the subjects would lean their torso forward. Thus, changes in the hip joint may have been adopted by the participants to prevent falling backward. It is noteworthy that a portion of the increase in joint work when using the exoskeleton was required merely to raise the CoM back to $H_{standing}$.

C. Energy Balance During the Upward Movement Approximated the Jump Height

An energy balance analysis was conducted to compare the total joint work and the difference in maximum jump height between the exoskeleton with no springs condition (Exo0) in the first session and the condition with the highest spring stiffness (Exo105S2) in the second session. Each jump had two energy components: one to move the CoM from the UPM (which is the lowest point in jumping) to a standing position and another to move the CoM from the standing position to maximum jump height. Assuming that rotational, horizontal kinetic, and vibrational energy loss, and error due to rigid body representation [46] was very small between the two jumps, the difference in joint work between the two conditions, Exo105S2 and Exo0, can then be formulated as

$$\Delta W = mg\left(\Delta H_{\min,2} + \Delta H^{p}_{\max,2}\right) - mg\left(\Delta H_{\min,0} + \Delta H_{\max,0}\right). \quad (6)$$

Rearranging this equation to predict the jump height in the second session yields

$$\Delta H^{p}_{\max,2} = \frac{140.5}{76 \cdot 9.806} - 0.43 + (0.34 + 0.38) = 0.469 \text{ m} = 46.9 \text{ cm} \quad (7)$$

where $\Delta H^{p}_{max,2}$ is the predicted jump height with the exoskeleton; ΔW is the difference in total joint work between the two jumping conditions; g is acceleration due to gravity (9.806 m/s^2); and m is the average mass of the participants (73 kg) plus the mass of the exoskeleton (3 kg), giving a total of 76 kg. It should be recalled 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), and also noted that subscripts 2 and 0 refer to Exo105S2 and Exo0, respectively. In this analysis, the jump height $\Delta H^{p}_{max,2}$ is predicted using the joint work and the heights obtained from the experiments. The expected jump height under the Exo105S2 condition was 46.9 cm, whereas the actual height achieved in the motion capture data was 45.9 ± 7.3 cm (mean ± S.D.). This result confirms the validity of the energy balance analysis.

D. Room for Improvement

Next, we examined the difference between the jump height without the exoskeleton and the jump height when wearing the exoskeleton as a deadweight, i.e., with no springs attached (Exo0). In this case, there was a small difference in the marker setup (detailed in the method section) for jumps with the exoskeleton and those without the exoskeleton. In addition, the mass of the exoskeleton was added to that of the thigh and shank. Consequently, there was a difference between the two models used in the inverse dynamic calculation, which could lead to additional differences in the work calculation [47], [48]. Therefore, a different calculation was used for the comparison of the jump height in the two conditions calculation based on the amount of energy needed to lift the exoskeleton mass (3 kg) to the jump height achieved in Exo0, which was calculated as follows:

$$W_{m_{exo}} = m_{\text{exo}} \cdot g \cdot \Delta H_{\text{max},0} = 0.434 \cdot 3 \cdot g = 12.77\ J \quad (8)$$

where $W_{m_{exo}}$ is the energy required to lift the exoskeleton to the jump height, m_{exo} is the mass of the exoskeleton (total for both legs), and $\Delta H_{max,0}$ is the jump height obtained when the participants jumped without the exoskeleton. Thus, the energy required to lift the exoskeleton mass would have decreased jump height by

$$\Delta H_{Gained} = \frac{W_{m_{exo}}}{m_h g} = \frac{12.77}{73g} = 1.8\ cm. \quad (9)$$

However, the actual difference in jump height between the Exo0 (no springs) and NoExo1 conditions in the first session was 4.5 cm, a value significantly greater than 1.8 cm. This difference between the expected height loss and the actual height difference between jumps in Exo0 and NoExo1 might indicate that not all changes in joint work translate into a difference in jump height. The height difference could be explained by the limitations of the exoskeleton, such as a lack of optimal fit for the user (all participants wore the same exoskeleton). A sub-optimal fit might result in energy loss in the form of energy used to compress the shank and thigh. Another possible explanation is that the Velcro straps and the arches would squeeze the leg muscles, causing motion restriction and external pressure, and consequently lower the peak output power of the participants, as intermuscular pressures can reduce muscle force [49]. Thus, this might be indirect evidence of the reduction of force due to external pressure. A custom exoskeleton for each participant [1] could potentially provide superior energy transfer between the exoskeleton and the user, reducing localized restriction and external pressures, and consequently, facilitate higher jumps. Furthermore, it is possible that the exoskeleton would reduce the degree of freedom in the biological knee joint, thereby lowering the efficiency of the jump mechanics.

The 105 N·m exoskeleton spring moment was designed to provide an additional moment equivalent of about 33% [11]–[13], in which the participants were professional athletes with body masses of ∼80 kg. However, the participants in our study were not professional athletes and their weight averaged approximately 73 kg, with a peak knee moment of approximately 200 N·m (for both knees). Thus, in the second session, spring stiffness provided approximately 50% of the biological knee capability. In the second session of this study, Exo105S2 showed that the work provided by the biological knee was 25% that of the total knee work. This was an improvement over the first experimental condition, Exo105S1, under which the biological knee contributed only 16% of the total knee work.

Comparing these findings with simulated human jumping using a passive exoskeleton [23] based on a model, the results of the simulation predict that springs providing approximately 50% of the peak moment of the biological knee would contribute approximately 35% of the biological work to the total knee work. This outcome would be 10% more than in the experiment. Thus, it might be possible to improve jump height if exoskeleton users were better trained to jump with the device. Furthermore, this training might produce a shift in the force–velocity curve of the muscle [50], [51].

Additional improvements might come from exploiting differences in the techniques employed when jumping with and without the exoskeleton. During a vertical jump with the exoskeleton, the participants had to find the optimal squat position for optimal stretching of the springs. Consequently, they remained in the squat position for a longer time relative to the NoExo conditions. Thus, jumps without the exoskeleton were akin to countermovement jumps, whereas jumps with the exoskeleton were akin to squat jumps (Supplementary Fig. S6). The difference between the two techniques is that in the countermovement, on reaching the UPM, the participant immediately extends the knees and hips, lifting into a vertical jump. However, in the squat technique, the participant remains in this position (the UPM) for some time before beginning the upward motion. In our study, under the *no exoskeleton* condition of the second session, the duration of the motion from standing to UPM was 0.85 ± 0.34 s. Under the exoskeleton condition of the same session, the duration was 2.65 ± 1.85 s. According to multiple studies, countermovement jumps are almost always higher than squat jumps [11], [52]–[54]. Komi *et al.* [53] suggested that the height gain is due to greater storage and more effective utilization of elastic energy in the muscle–tendon units. They posited that the tendinous tissues store elastic energy during downward movement and then utilize that energy during the upward movement. However, several studies have recently concluded that storage and utilization of elastic energy are not the main differentiators of countermovement and squat jumps [52], [55]–[57] because significantly more energy is lost as heat during a countermovement jump than during a squat jump. Bobbert *et al*. [52] argued that the primary benefit of countermovement is that it allows the muscles to build up a high level of active state and greater force before they start contracting, thereby allowing the muscles to produce more work. Therefore, future studies should examine jumping with an exoskeleton using the countermovement strategy to better understand human–exoskeleton interaction and potentially increase jump height.

E. Limitations and Future Work

Passive exoskeletons are lighter and cheaper, and like other passive exoskeletons, the device in this study was designed for only one function (jumping). Thus, a different design is needed for an exoskeleton device that can be useful for several tasks. For example, this could be a design with the option to engage and disengage the spring as a function of the task being performed (e.g., for walking, engage springs during the stance phase to support the body mass and disengage during the swing phase). Further, the power density of electrical motors has been increasing dramatically over recent years. In the future, this development will enable low-mass active exoskeletons that can produce the required torque and power, with the advantage of adjustable assistance profiles based on the task.

Our findings may inform the design of active exoskeletons for walking and running. There are several studies that investigate the best assistance profiles for walking [2], [58], [59]. The profile used in our experiment induces an increase in jump height, making it a potential first reference for feasible active exoskeletons. Similar to the knee's natural moment, the moment profile of the exoskeleton in this study has the largest magnitude at the beginning of the upward motion, which decreases toward the takeoff phase (Supplementary Fig. S4).

V. Conclusion

The study findings demonstrate that a passive knee exoskeleton can augment vertical jump height, with a 6.4% gain in jump height achieved using the exoskeleton compared to jumping without the study device. Our findings emphasize the need for training on how to use the exoskeleton to increase vertical jump height. We believe that this is the first study to show that an exoskeleton can be used to improve vertical jump height. It should be noted that just by wearing the exoskeleton as a dead weight, the jump height reduced by approximately 10%. An energy balance analysis and consideration of different potential jumping strategies suggest that jump height can be further improved beyond the results achieved in this study. Thus, future studies should focus on exploring devices with a better fit for the user, additional jumping techniques (including countermovement), and longer training durations.

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