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REVIEW OF SCIENTIFIC INSTRUMENTS **86**, 095107 (2015)

Design of a simple, lightweight, passive-elastic ankle exoskeleton supporting ankle joint stiffness

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In this study, a passive-elastic ankle exoskeleton (PEAX) with a one-way clutch mechanism was developed and then pilot-tested with vertical jumping to determine whether the PEAX is sufficiently lightweight and comfortable to be used in further biomechanical studies. The PEAX was designed to supplement the function of the Achilles tendon and ligaments as they passively support the ankle torque with their inherent stiffness. The main frame of the PEAX consists of upper and lower parts connected to each other by tension springs (N = 3) and lubricated hinge joints. The upper part has an offset angle of 5° with respect to the vertical line when the springs are in their resting state. Each spring has a slack length of 8 cm and connects the upper part to the tailrod of the lower part in the neutral position. The tailrod freely rotates with low friction but has a limited range of motion due to the stop pin working as a one-way clutch. Because of the one-way clutch system, the tension springs store the elastic energy only due to an ankle dorsiflexion when triggered by the stop pin. This clutch mechanism also has the advantage of preventing any inconvenience during ankle plantarflexion because it does not limit the ankle joint motion during the plantarflexion phase. In pilot jumping tests, all of the subjects reported that the PEAX was comfortable for jumping due to its lightweight (approximately 1 kg) and compact (firmly integrated with shoes) design, and subjects were able to nearly reach their maximum vertical jump heights while wearing the PEAX. During the countermovement jump, elastic energy was stored during dorsiflexion by spring extension and released during plantarflexion by spring restoration, indicating that the passive spring torque (i.e., supportive torque) generated by the ankle exoskeleton partially supported the ankle joint torque throughout the process. © *2015 AIP Publishing LLC.* [http://dx.doi.org/10.1063/1.4930561]

I. INTRODUCTION

Lower extremity flexibility allows humans to perform various dynamic movements, such as walking, running, and jumping.[1–4] However, a wide range of joint motion necessarily entails energy costs because some level of muscle power must be supplied to initiate and maintain movement. Among the joints involved in the power generation for this movement, the ankle joint is one of the major lower limb joints producing large joint torques.[5–8] For example, during normal walking and running, the ankle produces a larger peak torque and performs more positive work than other joints (e.g., the knee and hip), indicating that the ankle plantar flexors provide the majority of the mechanical work.[5] Thus, the ankle joint can be considered a candidate body part for developing a wearable orthotic device.

Many ankle exoskeletons have been developed to enable humans to reduce their energy costs during locomotion, and they can be grouped into two major types, i.e., powered and unpowered ankle exoskeletons, according to the presence of an active controller. (1) Powered ankle exoskeletons: pneumatically powered ankle exoskeletons controlled by the user's own soleus electromyography were developed to study human locomotor adaptation[9] and the effect of mechanical assistance at the ankle joint on the metabolic cost of walking.[10] Bilateral exoskeletons controlled via a feedforward algorithm triggering the onset and offset of pneumatic muscle actuation were constructed to examine whether subjects showed neuromotor and metabolic adaptation during a 24 min walk.[11] Portable powered ankle-foot orthotic systems were also developed to provide both plantar flexor and dorsiflexor torque assistance via a bidirectional pneumatic rotary actuator.[12] (2) Unpowered ankle exoskeletons: experimental studies have shown that parallel assistance to a muscle with appreciable series elasticity can reduce the soleus muscle force but does not work when hopping with exoskeleton assistance,[13] implying that elastic ankle exoskeletons may not be effective in reducing energy consumption because of the increase in the plantar flexor muscle fiber velocity.[14] However, model predictions have shown that there is a trade-off between metabolic cost minimization and enhanced mechanical performance.[15] A recent study also showed that the metabolic rate of human walking can be reduced by a lightweight elastic ankle exoskeleton that acts in parallel with the user's calf muscles.[16]

Passive-elastic mechanisms for energy-efficient bipedal locomotion have been reported in several studies on cursorial animals. Ostriches generate 120% more stance-phase mechanical joint power via the release of passive-elastic energy

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compared with humans, whereas their positive muscle fiber power is 35% lower than that of humans.[17] These differences may be primarily due to a higher capacity for the storage and release of elastic energy in ostriches, in which the elastic mechanical power occurs nearly exclusively at the tarsometatarso-phalangeal joint. In addition to the importance of spring-like muscle function, reducing metabolic energy by using ligaments as a passive leg-stabilizing mechanism can also be an effective locomotor endurance strategy.[18]

Applying the passive-elastic mechanisms of spring-like muscles, tendons, and ligaments to the design of the ankle exoskeleton, a simple, lightweight, passive-elastic ankle exoskeleton (PEAX) was developed in the present study using a one-way clutch mechanism, which enables mimicking the function of the Achilles tendon and ligaments as they passively support the ankle torque with their inherent stiffness.

II. METHODS

A. Mechanical design

A PEAX was designed to supplement the function of the Achilles tendon and ankle ligaments as they passively support the ankle torque with their inherent stiffness (Fig. 1). The main frame of the PEAX consists of upper and lower parts connected to each other by tension springs (N = 3) and lubricated hinge joints (Fig. 2). The upper part, which can be attached to the subject's shank, has an offset angle of 5° with respect to the

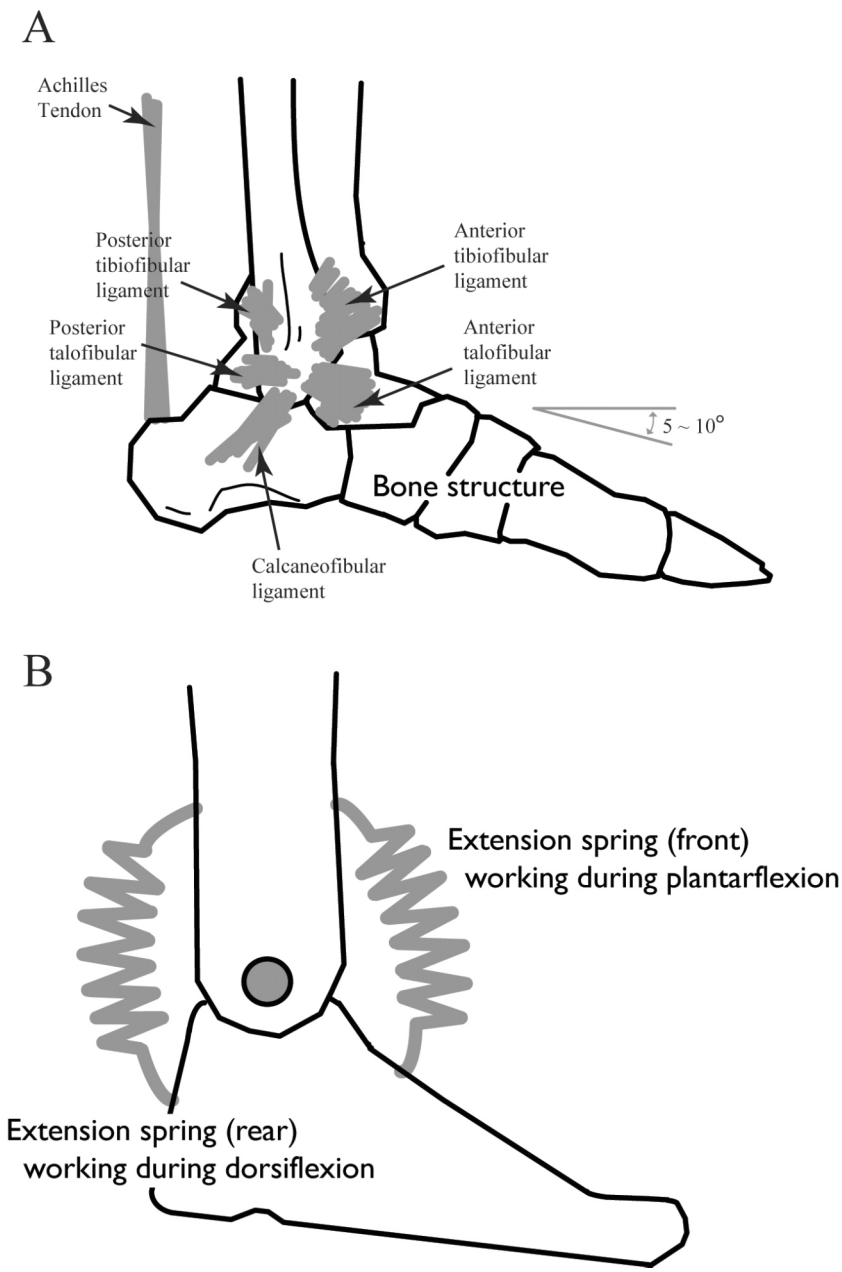

FIG. 1. (a) Simplified anatomy of the foot and ankle: bone structure, Achilles tendon, and ligaments in the sagittal plane. The ankle is in a resting posture (i.e., neutral position) of approximately 5°–10° of mild plantarflexion. (b) Schematics of an ankle/foot model consisting of two rigid links and two passive extension springs (i.e., front and rear in the sagittal plane) without active controllers. The rigid links indicate lower body segments, such as the foot and shank, whereas the extension springs represent the function of the Achilles tendon and ligaments as they passively support the ankle torque with their inherent stiffness.

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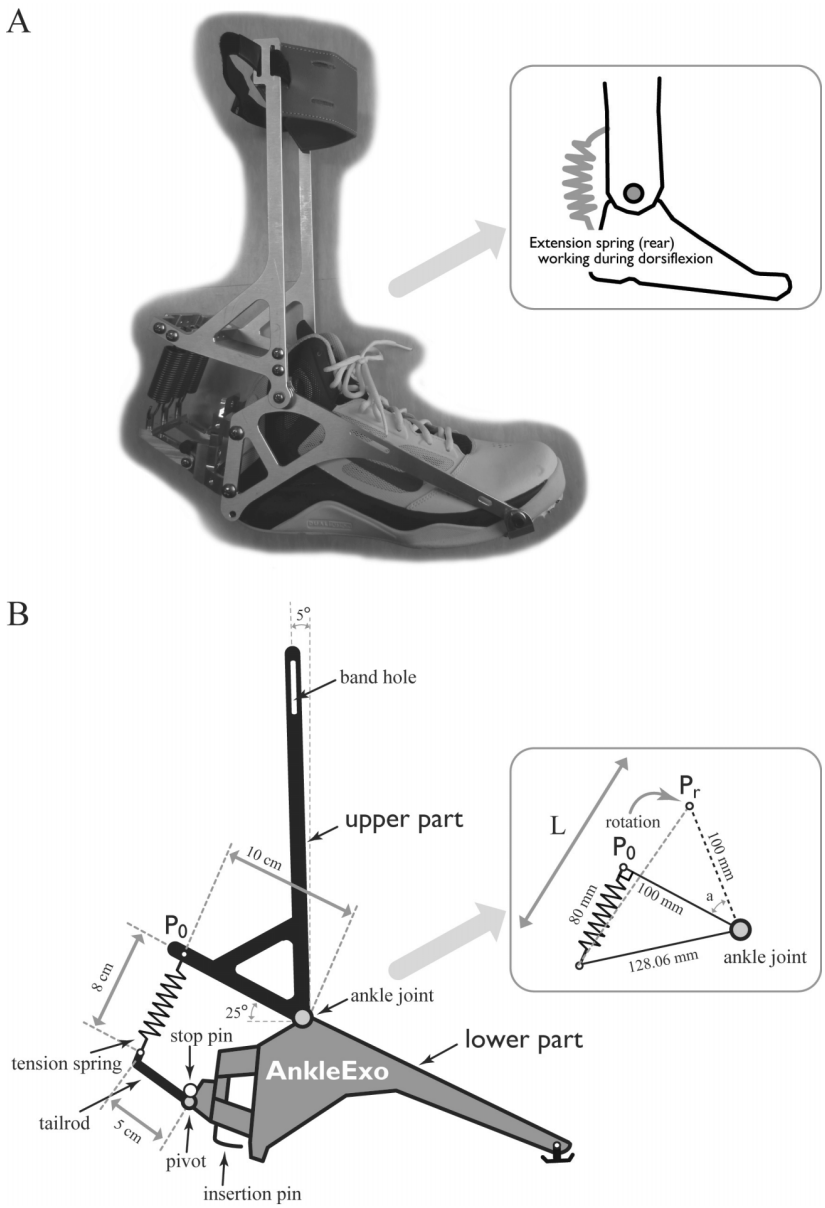

FIG. 2. Mechanical design of the passive-elastic ankle exoskeleton: (a) photograph of the ankle exoskeleton integrated firmly with a shoe and (b) schematic with some numerical values. As also shown in Fig. 1(a), the upper part of the ankle exoskeleton has an offset angle of 5° with respect to the vertical line. Each spring has a slack of 8 cm and connects the tailrod to the upper part in the neutral position. These spring structures can selectively strengthen the ankle joint stiffness by supporting the function of only the rear extension spring (see Fig. 1(b); inset). The tailrod freely rotates with low friction but has a limited range of motion due to the stop pin working as a one-way clutch, resulting in the tension springs storing only the elastic energy due to the ankle dorsiflexion when triggered by the stop pin at the neutral position. Each tensional spring was calibrated using different loading setups; then, spring displacement, force, and torque as a function of the dorsiflexion angle ("a"; inset) with respect to the vertical line were calculated based on the simple geometry (inset).

vertical line when the springs are in their resting state. Each spring has a slack length of 8 cm and connects the upper part to the tailrod of the lower part in the neutral position. The tailrod freely rotates with low friction but has a limited range of motion due to the stop pin working as a one-way clutch (Figs. 2 and 3).

The PEAX was designed to be firmly integrated with ready-made shoes (Dual Fusion BB II, Nike, US) without using bolts (Fig. 2). Because the PEAX fits the shape of the footwear well, only one insertion pin was needed to fix the exoskeleton to the footwear. Only two additional bolts were used to provide double-checked locking of the front of the lower part, and a leather pad was fastened around the subject's thigh.

The frame structures of the PEAX were made of aluminum alloy 7075 with a mass of 0.58 kg, and the total exoskeleton structure (i.e., the exoskeleton frame, shoe, springs, and thigh pad) weighed 1.08 kg (Table I). The resultant spring constant of the parallel spring sets was 3700 N/m as additive stiffness to an ankle joint, where the spring constant of each of the three springs was 1233 N/m.

B. Evaluating the effects of additional foot mass on vertical jump height

Countermovement jumps with the hands on the hips without wearing the ankle exoskeleton were performed to

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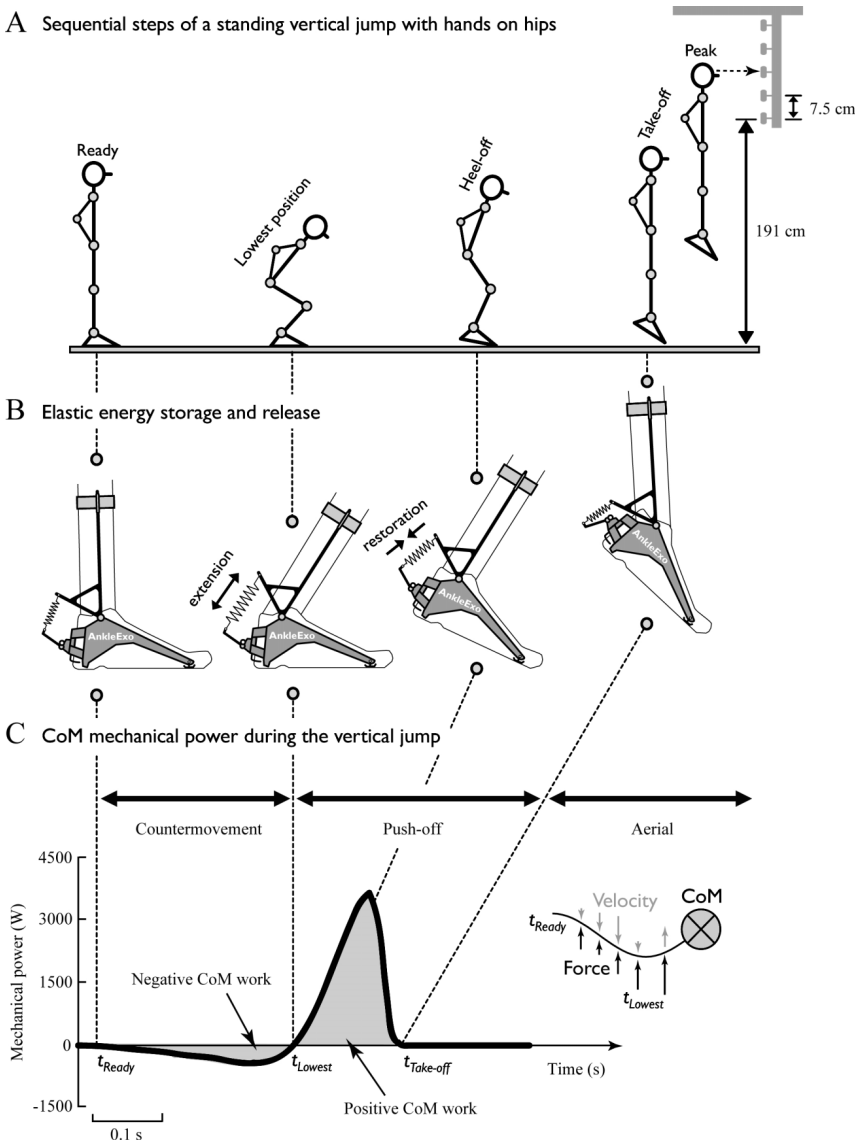

FIG. 3. (a) Simplified steps of a countermovement jump with hands on hips in the sagittal plane. (b) Elastic energy storage and release mechanism of the passive-elastic ankle exoskeleton. Each illustration corresponds to the above step in panel (a), connected with a dotted line. (c) CoM mechanical power during the countermovement jump. Negative CoM work (shaded area below the zero line) is performed during the countermovement phase because of the lowering motion from standing upright to the lowest position, whereas positive work (shaded area above the zero line) is performed during the push-off. The time course of the CoM position between ready and heel-off is shown in the right panel, with the directions and magnitudes of the CoM velocities (in gray) and applied forces (in black) shown.

estimate the theoretical effects of increasing foot device mass (i.e., ankle exoskeleton mass) on vertical jump height (Fig. 3(a)).

Five healthy young subjects (5 males, mean age: 27 ± 4 yr, mean body mass: 68 ± 5 kg, mean height: 178 ± 4 cm) who reported no history of balance disorder or major leg injuries participated in this study. All of the subjects signed an informed consent form approved by the Institutional Review Board of the Korea Advanced Institute of Science and Technology (KAIST) prior to the test. The subjects were instructed to stand upright and jump straight up to five different levels ranging from approximately 10% to 35% of their body height

TABLE I. Specifications of the ankle exoskeleton (one side).

Item	Material	Quantity	Unit
Exoskeleton frame (without a shoe)	Aluminum alloy 7075	580	g
Shoe	Leather and synthetic	340	g
Extension spring (K = 1230 N/m)	Stainless steel	3	ea
Thigh pad	Leather	1	ea
Total weight (frame + shoe + springs + pad)		1.08	kg

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(Fig. 3(a)). The lowest level was 191 cm above the ground, and the other levels were placed at equally spaced intervals of 7.5 cm. Black markers attached to a ceiling pole were used to guide the subjects to the corresponding heights. Prior to the regular tests, the subjects rehearsed during several pilot trials to become accustomed to reaching the target elevations.

The kinematic data (i.e., three-dimensional position) of the optical markers attached to the subject's sacrum (L5) and the kinetic data (i.e., ground reaction forces (GRFs) and moments) were recorded at a sampling rate of 200 Hz using four motion capture cameras (Hawk®, Motion Analysis, US) and a force plate (AccuGait®, AMTI, US), respectively. The vertical GRFs were time-integrated to estimate the velocity and position of the center of mass (CoM), and synchronized data for the sacral marker were used to determine the integral constants.[19–22] The time integrals of the impulsive force generated during the countermovement jump were then used to determine the peak vertical jump height (H_{peak}) based on the impulse-momentum method as follows:

$$V_{to} = \frac{1}{M} \cdot \int_{t_0}^{t_{to}} (F_v - M \cdot g) dt, \tag{1}$$

$$t_{peak} = \frac{V_{to}}{g} + t_{to}, \tag{2}$$

$$H_{peak} = V_{to} \cdot (t_{peak} - t_{to}) - \frac{1}{2} \cdot g \cdot (t_{peak} - t_{to})^2 + CoM_v(t_{to}) - CoM_v(t_0), \tag{3}$$

where V_{to} represents the take-off velocity, M represents the body mass, F_v represents the vertical GRF, g represents gravity, t_0 represents the initial time in the ready position, t_{to} represents the time required for take-off from the ready position, t_{peak} represents the time required to reach the peak position from the ready position, and CoM_v represents the vertical CoM displacement measured from the sacral marker (Fig. 3(a)). To ensure that the vertical jump heights were appropriately estimated, the motion capture data were used to confirm the peak values as follows:

$$H_{peak} = CoM_v(t_{peak}) - CoM_v(t_0). \tag{4}$$

The optical marker positions and GRFs were 5th-order Butterworth low-pass filtered with cutoff frequencies of 10 Hz for the motion capture data and 30 Hz for the force plate data.

The changes in the reduced vertical jump heights were simulated as functions of the original jump height and foot device mass (Fig. 3(c)). The reduced vertical jump heights were estimated based on the impulse-momentum method by adding the foot device mass (i.e., ankle exoskeleton mass) to the entire body mass without changing the impulse generated at a given original jump height.

C. Pilot jumping tests with ankle exoskeleton

To evaluate whether there were any obstructions when wearing the device, pilot subjects were instructed to jump vertically while wearing the ankle exoskeleton. During the pilot trials, the ankle moments were recorded at a sampling rate of 200 Hz using the force plate.

III. RESULTS

A. Relationship between dorsiflexion angle and supportive ankle torque

The extension spring displacement (Fig. 4(a)), stored spring force (Fig. 4(b)), and passive spring torque (Fig. 4(c)) showed strong linear relationships ($R^2 = 0.99$) with the dorsiflexion angle with respect to the vertical line. Due to the offset angle in the neutral position (Figs. 1 and 2), the initial force and torque have positive values when the subject stands upright (i.e., dorsiflexion angle = 0), where the slack length and resultant spring constant of the three extension springs are 8 cm and 3700 N/m, respectively. During dorsiflexion of the ankle joint, the passive spring torque (i.e., the supportive torque) increases up to 22 N/m as the dorsiflexion angle reaches 35°.

B. Effect of increasing foot mass on vertical jump height

The experimental impulse data values increased linearly with increasing vertical jump height, with the impulse data calculated based on the differences between impulses as functions of the ground reaction force and body weight (Figs. 5(a) and 5(b)).

As the foot device mass (i.e., the ankle exoskeleton mass) increases, the expected reduction in jump height increases for all of the original jump heights (Fig. 5(c)). For example, the reduction in jump height for an original jump height of 26 cm increases to nearly 2 cm with increases of up to 4 kg in the foot device mass, whereas the reduction in height for an original jump of 53 cm increases up to 5 cm with the same foot device. The expected reduction in jump height is greater for a higher jump than a lower jump at the same foot mass.

C. Portion of the supportive torque generated by the passive-elastic ankle exoskeleton

The passive spring torque (i.e., supportive torque) generated by the ankle exoskeleton partially supported the ankle torque as measured by the force plate during the countermovement jump (Fig. 6). The elastic energy was stored during dorsiflexion between the ready position and the lowest position by spring extension and was released during the plantarflexion phase between the lowest position and the heel-off position by spring restoration (Figs. 3(a) and 3(b)). The amount of ankle torque was larger than that of the supportive torque during the entire process, with the supportive torque ending shortly before take-off (Fig. 6).

IV. DISCUSSION

We presented a new design of a simple, lightweight, unpowered ankle exoskeleton supporting ankle joint stiffness and demonstrated that this exoskeleton is sufficiently lightweight and comfortable to passively support ankle push-off with the one-way clutch mechanism when the subject is performing a simple locomotor movement (i.e., vertical jumping).

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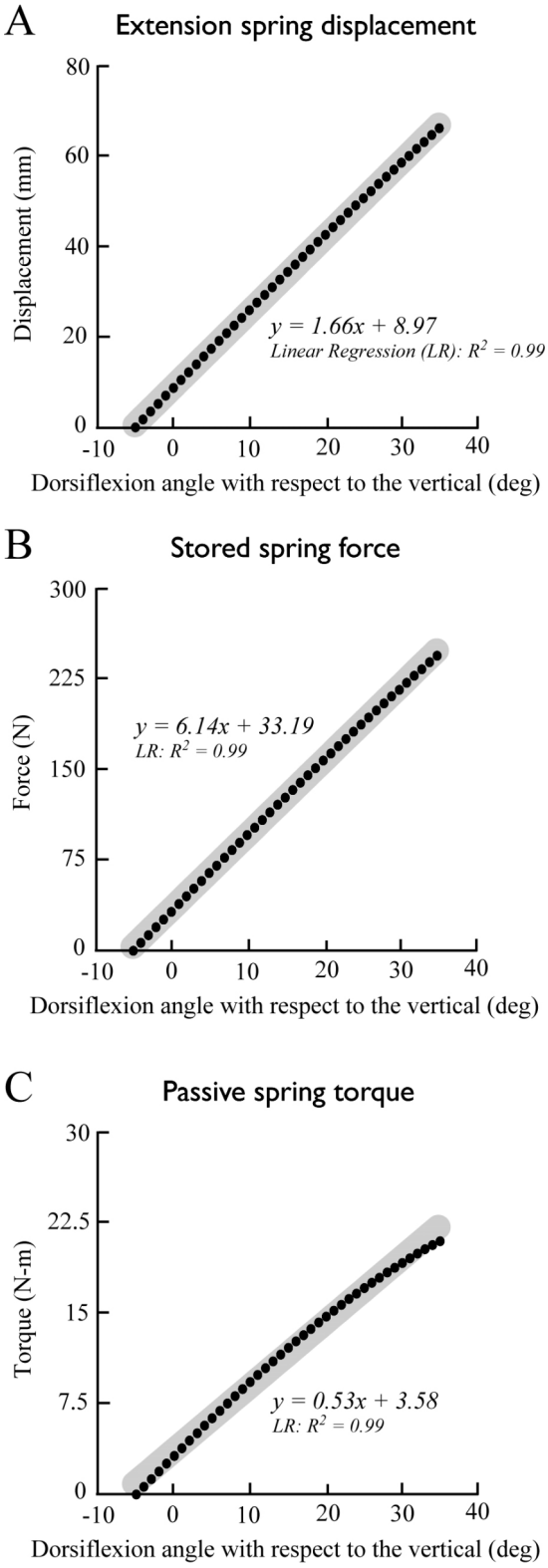

FIG. 4. (a) Extension spring displacement, (b) stored spring force, and (c) passive spring torque as a function of the dorsiflexion angle with respect to the vertical line (see Fig. 2(b)). Due to the offset angle in the neutral position, the initial force and torque have positive values when the dorsiflexion angle is zero, at which point the slack length and stiffness constant of the extension spring are 8 cm and 3700 N/m, respectively. The thick solid gray lines in (a)–(c) indicate the linear regression slopes of the simulation data (dotted lines) corresponding to each value (i.e., spring displacement, force, and torque, respectively) as a function of the dorsiflexion angle. The full equations for the curve fits are displayed in the form of $y = ax + b$ with goodness-of-fit data.

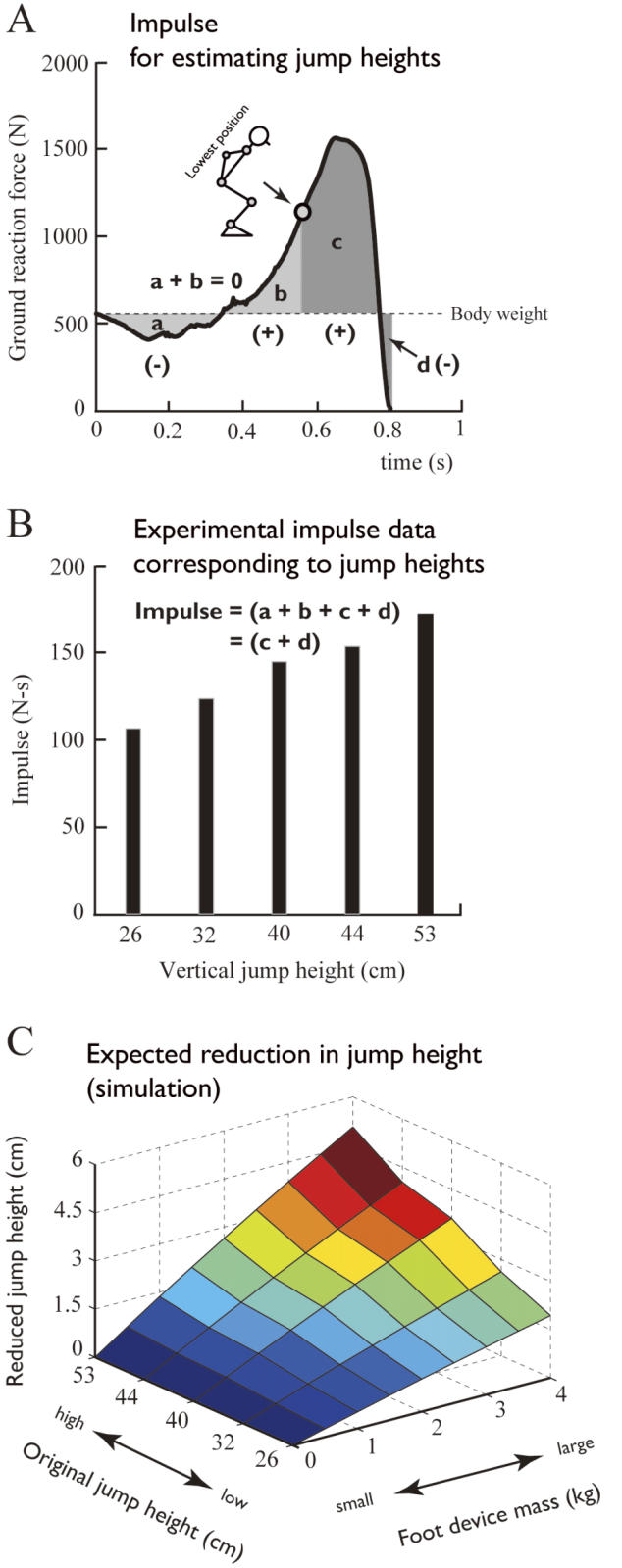

FIG. 5. (a) Time course of ground reaction force data during the countermovement jump for a representative subject (gender: male, age: 32 yr, body mass: 60 kg, body height: 170 cm). Shaded areas indicate the differences between impulses by the ground reaction force and body weight. (b) Empirical impulse data corresponding to vertical jump heights. (c) Simulation of the change of the reduced vertical jump height as a function of the original jump height and foot device mass (i.e., ankle exoskeleton mass). The reduced vertical jump heights were estimated based on the impulse-momentum method by adding the exoskeleton mass to the entire body mass without changing the impulse generated at a given original jump height.

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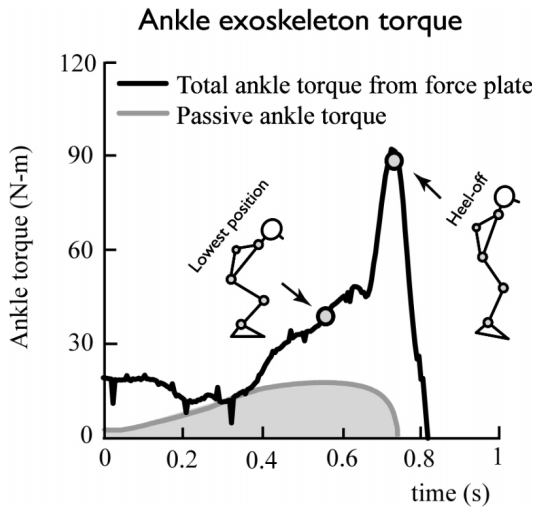

FIG. 6. Ankle torque measured by a force plate (black solid line) and passive spring torque generated by the ankle exoskeleton (gray sold line) during the countermovement jump. Gray circles represent the lowest position and heel-off.

A. Design of the simple lightweight ankle exoskeleton

The PEAX was designed to weigh approximately 1 kg. Considering only the effects of the additional mass at the end of the leg (i.e., foot), an additional 2 kg for both legs may theoretically reduce the vertical jump height by less than 3 cm for an original jump height of 53 cm (approximately 92% of the subject's maximum vertical jump height) for the pilot subject (body mass: 60 kg) (Fig. 5(c)). In addition to the lightweight design, the PEAX was simply and firmly integrated with ready-made shoes (Dual Fusion BB II, Nike, US) because the aluminum frame of the PEAX aligns well with the 3D surface shape of the footwear (Fig. 2(a)). After using the ankle exoskeleton, all of the pilot subjects reported that the PEAX was comfortable for jumping, walking, and running, and the subjects were able to almost reach their maximum vertical jump heights while wearing the PEAX.

B. Passive-elastic ankle exoskeleton with a one-way clutch for vertical jumping

Because the CoM work performed during the downward action between the ready position and lowest position is negative (Fig. 3(c)), the positive torque generated by the PEAX supported the ankle joint motion during this period (Fig. 6): the amount of supportive ankle torque (sign: +) provided by the PEAX was smaller than that of the ankle torque (sign: +) measured by the force plate during the entire process, indicating that the supportive torque could be part of the ankle torque. If the sign of the spring torque is different from that of the corresponding joint torque (measured without assistance when performing the same movement), parallel assistance with passive springs may produce a serious inconvenience. For example, the PEAX could not support voluntary ankle dorsiflexion above the ground because the spring torque acts as an obstacle during the entire process.

The PEAX is equipped with a one-way clutch system using a stop pin such that the tension springs store the elastic energy only due to ankle dorsiflexion when triggered by the stop pin (Figs. 3(a) and 3(b)). This clutch mechanism also has the advantage of preventing any inconvenience during ankle plantarflexion because it does not limit the ankle joint motion during this phase. Therefore, the PEAX strengthens the stiffness of the ankle-foot ligaments only during ankle dorsiflexion because it passively supports the ankle torque with its spring stiffness.

C. Targeted user populations of the passive-elastic ankle exoskeleton

The targeted populations may vary from normal individuals (e.g., subjects with no history of balance or leg injury) to individuals with leg injuries (e.g., persons with Achilles tendon injury or patients who require support for stronger push-off). We need more evidence and/or experimental data (future work) to determine whether the passive-elastic ankle exoskeleton can help subjects with leg injuries walk naturally or efficiently; however, a recent study has shown that the metabolic rate of human walking can be reduced by a lightweight elastic ankle exoskeleton.[16] Based on their work and several other studies reporting a trade-off between metabolic cost minimization and enhanced performance (under exoskeleton assistance),[15] the PEAX could potentially be used with various subjects to support the energetics and/or behaviors of human locomotion if the passive joint stiffness is appropriately selected.

D. Limitation of the current passive-elastic ankle exoskeleton

Strengthening the ankle joint stiffness during dorsiflexion is not always needed to support the ankle torque. When attempting to flex the ankle joint above the ground, some level of resistance provided by the artificial stiffness could be an obstacle, resulting in uncomfortable movement. However, the PEAX might not produce a serious inconvenience during normal walking and/or running because the working range of the one-way clutch system seldom overlaps with the range of motion for foot clearance during the swing phase.

E. Future research directions

We did not use force sensors to measure the spring force data during the pilot tests, with the following assumptions: (1) jumping is a type of simple low-frequency behavior in the sagittal plane, such that the motion was assumed to be nearly quasi-static, and (2) the mechanical joint frictions were negligible. However, if the force data were recorded from a force sensor in parallel with the spring, more robust conclusions could be made regarding the added assistance of the PEAX.

A one-way clutch mechanism and lightweight design were introduced in this study, but unexplored areas remain regarding the ankle exoskeleton and its mechanical, energetic, and physiological effects when integrated with humans. For example, the PEAX developed in this study could be utilized

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for several biomechanical studies, such as studies of the following:

- stiffness (i.e., spring constant) optimization for a maximum vertical jump;
- metabolic effects of wearing the ankle exoskeleton during walking and/or hopping;
- mechanical effects of the ankle exoskeleton during walking;
- offset angle optimization during inclined walking; and
- application to the design of a powered ankle exoskeleton.

F. Summary

The advantages of the simple, lightweight, PEAX are as follows: (1) the PEAX is sufficiently lightweight and comfortable for use in further studies of human locomotion, weighing only approximately 1 kg; (2) the PEAX can be manually adjusted to change the supportive stiffness of the ankle joint by changing the combination of the extension springs; and (3) the one-way clutch mechanism selectively strengthens the ankle joint stiffness only during ankle dorsiflexion, without an additive energy input.

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The authors declare no conflicts of interest.

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