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RESEARCH ARTICLE

The role of elastic energy storage and recovery in downhill and uphill running

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SUMMARY

In level running, humans and other animals store and recover elastic energy during each step. What role does elastic energy play during downhill and uphill running? We measured the fluctuations of the mechanical energy of the center of mass (CoM) of 15 human participants running at 3 m s^{-1} on the level, downhill and uphill on a force-measuring treadmill mounted at 3, 6 and 9 deg. In level running, nearly symmetrical decreases and increases of the combined gravitational potential and kinetic (GPE+KE) energy of the CoM indicated equal possible elastic energy storage and recovery. However, asymmetrical fluctuations during hill running indicate reduced maximum possible elastic energy storage and return. We analyzed mechanical energy generation and dissipation during level and hill running by quantifying the anatomically estimated elastic energy storage (AEEE) in the arch and Achilles' tendon using peak ground reaction forces and anatomical characteristics. AEEE did not change with grade. At shallow downhill grades, the body must generate mechanical energy, though it dissipates more than it generates. At steeper downhill grades, little to no energy generation is required and only mechanical energy dissipation must occur. The downhill grade at which mechanical energy must no longer be generated occurs at approximately –9 deg, near the metabolically optimal running grade. At shallow uphill grades, mechanical energy must be generated to raise the CoM, and at steeper grades, additional energy must be generated to offset reduced elastic energy storage and return.

Key words: slope, biomechanics, leg spring, energy generation, energy dissipation.

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INTRODUCTION

Level running is often likened to a bouncing ball (Cavagna et al., 1964; Margaria, 1976) or a resilient spring–mass system (Blickhan, 1989; McMahon and Cheng, 1990). These analogies accurately describe the energy-saving mechanism used by running humans and other animals. During level running, gravitational potential energy (GPE) and kinetic energy (KE) of the center of mass (CoM) fluctuations are symmetrical and in-phase. Theoretically, all of this energy could be stored elastically in the tendons and subsequently recovered (Cavagna et al., 1977). However, in downhill and uphill running, some net mechanical energy dissipation and generation, respectively, is required. Thus, it is not possible for all of the energy to be equally stored and recovered. The goal of our study was to investigate the role of elastic energy storage and recovery during downhill and uphill running.

Although the mechanical aspects of hill running have been investigated extensively in at least three previous studies, the role of elastic energy has not been thoroughly characterized. Minetti and colleagues measured mechanical work during human hill running at a range of speeds (Minetti et al., 1994). They reported that positive external work per unit distance decreased linearly with slope during downhill running and increased linearly with slope during uphill running. At hill angles steeper than –17 and +17 deg, exclusively negative and positive work, respectively, were performed. Iverson and McMahon used a mathematical model to study the mechanical behavior of the legs during hill running (Iverson and McMahon, 1992). They assumed that each stance leg behaved like a spring, regardless of the hill angle. In their model, the legs performed net negative or positive work on downhill or uphill angles, respectively, by changing leg stiffness at midstance. Neither of these studies reported GPE and KE fluctuations, nor did they quantify elastic energy storage and recovery. Our recent study examined elastic energy storage during shallow, 3 deg hill running (Snyder and Farley, 2011). We found that compared with level running, maximum possible elastic energy storage and return decreased during both downhill and uphill running. However, the percentage of positive power due to estimated actual elastic energy recovery, hereafter called anatomically estimated elastic energy storage (AEEE), increases during downhill running and decreases during uphill running (Snyder and Farley, 2011).

Our purpose in the present study was to evaluate the magnitude of elastic energy storage and recovery during both downhill and uphill running at multiple grades. We first calculated the maximum possible elastic energy storage and return (MPEE) from the mechanical energy fluctuations of the CoM. We predicted MPEE would be compromised during slope running for two reasons: (1) the inherent overall decrease or increase in GPE during the stance phase due to the downhill or uphill grade, respectively, and (2) the necessity to decrease or increase KE during the stance phase as a result of the effects of gravity during the aerial phase of downhill or uphill running, respectively. However, because the mechanical energy fluctuations of the CoM only give information about the maximum possible energy storage and return, we also calculated the AEEE based on ground reaction forces (GRFs) and previous anatomical measurements.

MATERIALS AND METHODS

Data were collected from 9 men and 6 women (mass 65.0±9.4 kg, mean ± s.d.). All of these healthy, recreational athletes gave written informed consent that followed the guidelines of the University of Colorado Human Research Committee.

Participants ran at $3\,m\,s^{-1}$ on the level, downhill and uphill on a force treadmill mounted to 3, 6 and 9 deg wedges (Gottschall and Kram, 2005; Gottschall and Kram, 2006; Kram et al., 1998). Because of the lengthy process of changing the treadmill angle, each participant completed experimental sessions on four different days. Randomizing the order was not a concern because participants completed sessions with at least a day of rest between sessions. At the beginning of each session, participants completed a 5 min warm-up on a level treadmill. They then ran for 1 min at their preferred step frequency on the force treadmill both downhill and uphill at the pre-determined grade, or on the level (Fig. 1). The collection period was chosen to facilitate the steep uphill angles. A shorter period would not have allowed the movement patterns to stabilize, and a longer period could have induced fatigue. We collected the normal and parallel components of the GRF data at 1000 Hz (LabView 4.0, National Instruments, Austin, TX, USA), and then analyzed the last 10 s of each trial.

After data collection, we filtered the GRF data and calculated the mechanical energy fluctuations of the CoM. The filter was a numerical fourth-order, zero phase-shift, low-pass Butterworth filter with a cut-off frequency of 20 Hz. We created a Matlab integration program based on the method of Cavagna (Cavagna, 1975) and modified it for hill running. In order to calculate the instantaneous GPE of the CoM, we combined the normal and parallel measurements into a global vertical force ($\mathbf{F}_{vertical}$) equal to ($\mathbf{F}_{normal}\cos\theta$)+($\mathbf{F}_{parallel}\sin\theta$). $\mathbf{F}_{normal}$ is the force perpendicular to the treadmill belt, $\mathbf{F}_{parallel}$ is the force parallel to the treadmill belt, and θ is the angle of the treadmill relative to the ground. We calculated the instantaneous vertical acceleration ($a_{vertical}$) equal to ($\mathbf{F}_{vertical}$–$m\boldsymbol{g}$)/m, where m is equal to the participant's body mass and $\boldsymbol{g}$ is equal to the gravitational acceleration, $9.81\,m\,s^{-2}$.

We calculated the instantaneous vertical velocity ($v_{vertical}$) of the CoM by integrating the vertical acceleration ($a_{vertical}$) with respect to time and adding an integration constant. For level running, we used the Cavagna method to determine the integration constant, knowing that the average vertical velocity over a complete step is zero. For hill running, we calculated the integration constant, knowing that the average vertical velocity over a complete step was equal to the $v_{tread}\sin\theta$, where v_{tread} is the velocity of the treadmill belt.

We calculated instantaneous vertical height ($h_{vertical}$) of the CoM by integrating the vertical velocity ($v_{vertical}$) with respect to time and adding an integration constant. For level running, we used the Cavagna method to determine the integration constant for this calculation by assuming that the CoM returns to the same vertical position at the end of each step. For hill running, we calculated the integration constant, knowing that over a complete step the CoM changes vertical height by an amount equal to ($v_{tread}\sin\theta$)$\times t_{step}$, where t_{step} is equal to the stance time and aerial time of one limb. Finally, we calculated the instantaneous GPE as $m\boldsymbol{g}h_{vertical}$.

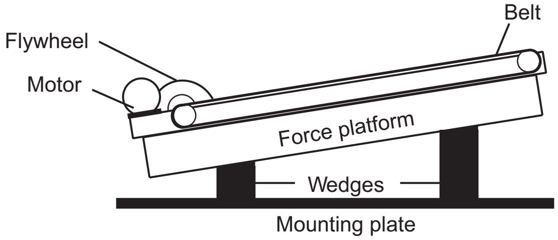

Fig. 1. Force-measuring treadmill mounted at 9 deg.

To calculate the instantaneous KE fluctuations of the CoM, we used the normal and parallel GRF measurements ($\mathbf{F}_{normal}$ and $\mathbf{F}_{parallel}$). First, we determined the instantaneous acceleration in each direction (a_{normal} and $a_{parallel}$) equal to ($\mathbf{F}_{normal}$–$m\boldsymbol{g}\cos\theta$)/$m$ and ($\mathbf{F}_{parallel}$–$m\boldsymbol{g}\sin\theta$)/$m$, respectively. Next, we calculated the normal and parallel instantaneous velocities (v_{normal} and $v_{parallel}$) by integrating the acceleration (a_{normal} and $a_{parallel}$) with respect to time and adding an integration constant that was adjusted for the hill angle. We calculated the integration constant by knowing that the average parallel velocity was equal to the v_{tread} and that the average v_{normal} was zero. Finally, we combined these normal and parallel velocities (v_{normal} and $v_{parallel}$) using the Pythagorean theorem to determine the resulting instantaneous velocity of the CoM and then KE, $0.5mv^2_{result}$.

We quantified the mechanical energy fluctuations per step, and averaged the stance and swing phases separately over all steps for each participant. Additionally, we calculated the decreases and increases in GPE, KE and combined (GPE+KE) energy (E_{com}). Maximum possible elastic energy storage was defined to be the difference between initial and minimum E_{com} during the stance phase and energy return was defined to be the difference between the ending and minimum E_{com} during the stance phase. MPEE was defined as the smaller of these two values.

After calculating MPEE, we determined an anatomically based estimate of the elastic energy (AEEE) that could be stored in the Achilles' tendon and the arch aponeurosis for each grade based on the GRFs using methods adapted from previous studies (Alexander and Bennet-Clark, 1977; Ker et al., 1987). These researchers used moment arm measurements to determine the forces in the arch and the Achilles' tendon based on GRFs. Alexander and Bennet-Clark then used calculations of the stress and length change in the Achilles' tendon to calculate strain energy in the tendon (Alexander and Bennet-Clark, 1977). Ker and colleagues used force–length curves for the tendon from cadaveric feet to determine stiffness in each structure for a given GRF, which could then be used to calculate elastic energy storage (Ker et al., 1987). Assuming similar relative moment arm measurements, we estimated the amount of force in the arch ($\mathbf{F}_{arch}$) and Achilles' tendon ($\mathbf{F}_{Ach}$) using $\mathbf{F}'$=($\mathbf{F}$/GRF$_{peak}$)GRF$'_{peak}$, where $\mathbf{F}$ indicates the force in the arch or Achilles' tendon, and GRF$_{peak}$ the peak perpendicular force. Primes designate our calculations and unmarked variables ($\mathbf{F}_{arch}$=4.7 kN, $\mathbf{F}_{Ach}$=6.4 kN, GRF$_{peak}$=1.9 kN) indicate values from the previous studies (Alexander and Bennet-Clark, 1977; Ker et al., 1987). Assuming the same stiffness, we calculated elastic energy storage in each structure using the formula $E'=E(\mathbf{F}'/\mathbf{F})^2$ (Snyder and Farley, 2011), where $\mathbf{F}$ indicates the force in the arch or Achilles' tendon, and E is elastic energy, 17 J for the arch and 35 J for the Achilles' tendon (Alexander and Bennet-Clark, 1977; Ker et al., 1987), and then summed together.

Finally, we analyzed these data across all conditions using a repeated measures design (ANOVA). We performed Newman–Keuls *post hoc* tests to ascertain the differences between conditions. Significance was defined as $P\leq0.05$.

RESULTS

During level running, the CoM combined energy (E_{com}=GPE+KE) decreased and increased during each step by an almost symmetrical

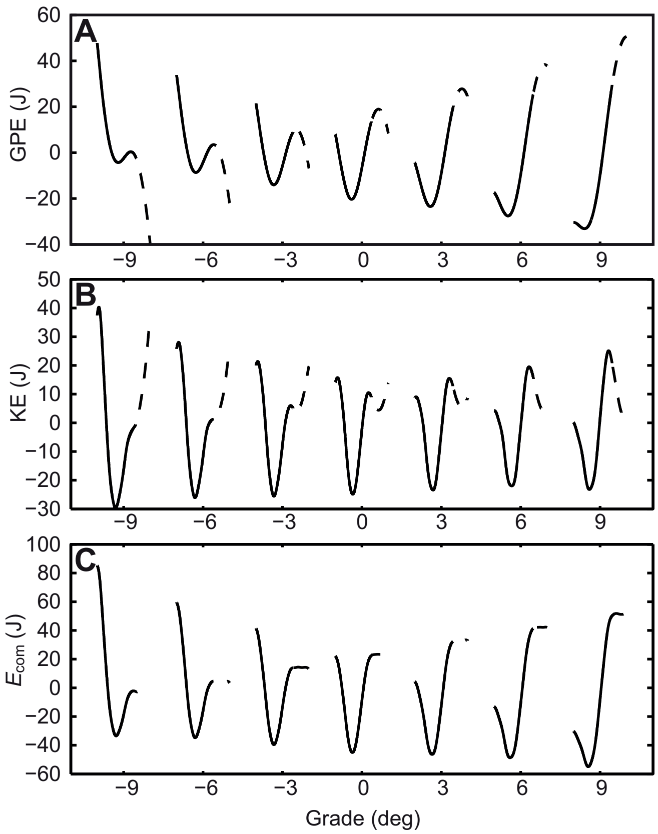

Fig. 2. Center of mass (CoM) mechanical energy *versus* time for a 54 kg participant. Solid lines indicate the stance phase and dashed lines indicate the aerial phase. (A) GPE, gravitational potential energy; (B) KE, kinetic energy; (C) E_{com}, combined (GPE+KE) energy.

85.1 and 84.9 J, reaching a minimum value at approximately the middle of the stance phase. Therefore, it was theoretically possible that all of the E_{com} lost by the CoM in the first half of stance was stored elastically and subsequently recovered during the second half of stance.

MPEE decreased at steeper hill angles, as demonstrated by the fluctuations of the E_{com} (Fig. 2, Table 1). At downhill angles of –9, –6 and –3 deg, E_{com} decreased by 110.4, 73.1 and 43.7 J (74, 59 and 40%), respectively, more than it subsequently increased (all values $P<0.001$), indicating that all of the energy increase could have come from elastic energy recovery and an MPEE of 37.8, 50.6 and 65.6 J. At uphill angles of +3, +6 and +9 deg, E_{com} decreased by 39.7, 69.0 and 102.5 J (39, 61 and 77%), respectively, less than it increased (all values $P<0.0001$), indicating that all of the energy increase could not have come from elastic energy recovery and an MPEE of 61.1, 44.6 and 29.8 J.

We found similar values of AEEE for all grades (Table 2) with a range of 31–37 J step^{-2}. However, because the combined energy necessary to lift and accelerate the body during the second half of stance ($E_{com(+)}$) changed drastically at each grade (Table 1), AEEE represented 98, 71, 54, 43, 35, 30 and 24% of the total positive mechanical energy per step needed at grades of –9, –6, –3, 0, 3, 6 and 9 deg, respectively.

DISCUSSION

As anticipated, mechanical energy fluctuations were asymmetrical during downhill and uphill running, reflecting decreases in the MPEE. However, AEEE was nearly constant across grades. During downhill running, some positive mechanical energy generation is still needed at shallow grades, though more dissipation occurs than generation. However, by –9 deg, the AEEE accounts for nearly all the necessary energy generation, indicating that little to no positive energy generation is necessary, but some controlled dissipation must occur (Fig. 3). During uphill running, at shallow grades, the AEEE is similar to that on the level, so positive energy generation is only needed to lift the CoM vertically. However, by +9 deg, the decrease in energy of the CoM during the first half of stance is slightly smaller than the AEEE, indicating that, at steeper slopes, the body needs to generate positive energy to both raise the CoM and offset the diminished MPEE (Fig. 3).

Our results suggest that both elastic energy use and muscular work contribute to the positive energy increases in level running. Though AEEE accounts for about 43% of the overall energy fluctuation during each step, the muscles must perform additional negative and positive work to lower and raise the center of mass. Further, there is an additional mechanical and metabolic cost associated with 'internal work', or moving the limbs relative to the CoM (Cavagna et al., 1964). Based on these findings, we can infer that the cost of both force production (Kram and Taylor, 1990) to facilitate elastic energy use and positive muscular work contributes to metabolic cost in level running.

These biomechanical results may offer some insight into the metabolic energy cost of running. It has long been known that metabolic energy cost is reduced during downhill running compared with level running at the same speed. It has been shown that running is least expensive at a downhill angle between –6 and –9 deg (Margaria et al., 1963; Minetti et al., 1994). As the downhill angle increases beyond this optimal grade, metabolic rate increases. Our results indicate that at –9 deg, on average, there is little to no energy generation required and only mechanical energy dissipation occurs (Table 2), whereas at –6 deg positive mechanical energy generation

Table 1. Mechanical energy fluctuations during stance

Grade (deg)	KE↓ (J)	KE↑ (J)	ΔKE (J)	GPE↓ (J)	GPE↑ (J)	ΔGPE (J)	E_{com} ↓ (J)	E_{com} ↑ (J)	ΔE_{com} (J)
–9	79.2	30.3	–48.9	69.8	8.3	–61.5	148.2	37.8	–110.4
–6	64.9	30.8	–34.0	59.0	19.9	–39.1	123.7	50.6	–73.1
–3	60.5	31.3	–29.2	49.0	34.5	–14.5	109.3	65.6	–43.7
0	46.8	39.4	–7.4	38.4	45.7	7.3	85.0	84.9	–0.1
3	32.7	42.6	9.8	28.6	58.6	29.9	61.1	100.8	39.7
6	28.0	44.2	16.2	17.4	70.3	52.9	44.6	113.6	69.0
9	24.9	49.6	24.6	6.7	84.6	77.9	29.8	132.3	102.5

Values represent means ± s.d. for all 15 participants. Up arrows indicate an increase in energy, whereas down arrows represent a decrease in energy.
KE, kinetic energy; GPE, gravitational potential energy; E_{com}, combined (GPE+KE) energy.
All downhill and uphill running conditions differed from level running ($P<0.0001$).

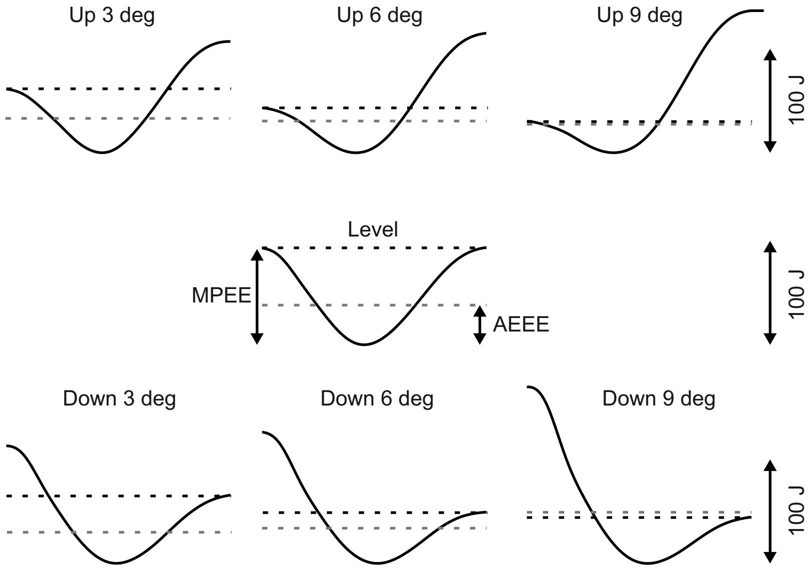

Fig. 3. Elastic energy storage and return, mechanical energy generation and mechanical energy dissipation change significantly with slope. These solid curves show the mechanical energy fluctuations of the CoM throughout stance. The black dashed lines represented the maximum possible elastic energy storage and return (MPEE). The gray dashed lines represent the anatomically estimated elastic energy storage (AEEE) based on ground reaction force and anatomical data for a typical participant (mass 70 kg). At moderate slopes (<6 deg), both mechanical energy generation and dissipation occur, though more generation occurs uphill and more dissipation occurs downhill. At around –9 deg, the AEEE reaches the energy decrease (increase) during the first (second) half of stance uphill (downhill). At steeper downhill slopes, the body must dissipate some of the elastic energy. At steeper uphill slopes, elastic energy storage decreases, so the body must generate additional energy to account for this decrease.

is still required. Further, while on average little to no energy generation is needed at –9 deg, for participants around 70 kg for whom the AEEE is likely most accurate, the grade at which positive power production is no longer needed occurs closer to –6 deg. It is only for participants with a lower body mass, for whom AEEE may not be as accurate, that power production is needed at steeper downhill grades. It is therefore possible that the minimum metabolic energy cost occurs between –6 and –9 deg because it is in the range within which elastic energy storage and recovery can account for all the necessary positive mechanical work. On steeper downhill grades, mechanical energy dissipation must occur, whereas on shallower downhill grades, though more mechanical energy is dissipated than generated, some positive mechanical energy must be generated during each step. Additionally, the relatively high and low efficiencies of positive and negative work production, respectively, likely contribute to the minimum cost occurring at a slightly shallower angle, as suggested previously (Minetti et al., 1994).

In contrast, metabolic cost is obviously greater during uphill than during level running. Margaria and colleagues showed that the relationship between uphill grade and metabolic cost is linear (Margaria et al., 1963). Some positive work must be performed to run on a level surface. However, the muscles must perform additional positive work to travel uphill, though some energy dissipation occurs during each step at shallower grades. At steeper uphill grades, the AEEE is slightly less than the MPEE, which, during uphill running, is equal to the decrease in energy during the first half of stance. This difference indicates that additional mechanical energy must be generated at steeper uphill grades to compensate for the diminished possible elastic energy storage (Table 2). This mechanical energy generation increases moderately at grades of 0, 3 and 6 deg, with values of 48.8, 65.6 and 78.9 J step^{-1}, respectively, and increases drastically at 9 deg to 101.0 J step^{-1}.

There are a number of factors that could account for the increased cost of running uphill in addition to a reduction in elastic energy storage and return. Because there is always some decrease in mechanical energy during a step at 9 deg, there is likely a similar return of elastic energy across grades *via* the stretch–shorten cycle (Bosco et al., 1982). However, to raise the CoM uphill, additional positive work must be generated by metabolically expensive concentric muscle actions. Roberts and Belliveau showed that there is a large increase in mechanical power production at the hip joint between level and uphill running, which likely increases the metabolic cost because of the large muscle volume of the hip extensors (Roberts and Belliveau, 2005).

Though sufficient for capturing the overall changes between level and graded running, our study naturally had some limitations. Because we studied the body as whole, we did not determine at which joints the muscles must generate more mechanical and metabolic energy in uphill running (DeVita et al., 2008). Further, although our results are consistent with those of Lichtwark and Wilson (Lichtwark and Wilson, 2006), we did not utilize ultrasound measurements of the tendon and muscle length changes. We also

Table 2. Elastic energy calculations

Grade (deg)	GRF_{peak} (N)	AEEE (J)	$E_{com(+)}$ (J)	AEEE/$E_{com(+)}$ (%)	MPEE (J)
–9	1575	37.2	37.8	0.98	37.8
–6	1555	36.0	50.6	0.71	50.6
–3	1549	35.5	65.6	0.54	65.6
0	1565	36.2	84.9	0.43	83.8
3	1548	35.3	100.8	0.35	61.1
6	1534	34.8	113.6	0.31	44.6
9	1457	31.4	132.3	0.24	29.8

GRF_{peak}, mean peak perpendicular ground reaction forces for each gradient; AEEE, estimated actual energy storage based on ground reaction and tendon forces; $E_{com(+)}$, total increase in mechanical energy per step for each gradient; AEEE/$E_{com(+)}$, percentage of positive energy accounted for by anatomically estimated elastic energy storage; MPEE, maximum possible elastic energy storage and return based on energy fluctuations.

did not include ankle angular excursions in the AEEE calculations, and the estimates provided were only for the arch aponeurosis and the Achilles' tendon. Finally, without metabolic data collected simultaneously, we can only infer how our mechanical findings may translate into metabolic changes.

Using multiple methods, we examined elastic energy storage and recovery in level, downhill and uphill running. Symmetric mechanical energy fluctuations in level running indicate that equal storage and recovery of elastic energy is possible. The asymmetry of the mechanical energy fluctuations indicates a decrease in MPEE with steeper grades. However, AEEE did not change significantly across grade. Downhill, AEEE remains less than MPEE until around –9 deg, slightly steeper than the angle that minimizes metabolic energy cost. Running uphill, moderate mechanical energy generation is needed at shallow grades and significant energy generation is involved at steeper grades to account for the reduced MPEE.

LIST OF ABBREVIATIONS

AEEE	anatomically estimated elastic energy storage
CoM	center of mass
E_{com}	combined gravitational potential and kinetic energy of the center of mass
$E_{com(+)}$	combined energy increase during second half of stance
GPE	gravitational potential energy of the CoM
GRF	ground reaction force
KE	kinetic energy of the CoM
MPEE	maximum possible elastic energy storage and return

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