Subjective valuation of cushioning in a human drop landing task as quantified by trade-offs in mechanical work

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25

26 **Abstract**

27 Humans can perform motor tasks in a variety of ways, yet often favor a particular
28 strategy. Some factors governing the preferred strategy may be objective and
29 quantifiable, (e.g. metabolic energy or mechanical work) while others may be more
30 subjective and less measurable, (e.g. discomfort, pain, or mental effort). Subjectivity
31 can make it challenging to explain or predict preferred movement strategies. We
32 propose that subjective factors might nevertheless be characterized indirectly by their
33 trade-offs against more objective measures such as work. Here we investigated
34 whether subjective costs that influence human movement during drop landings could
35 be indirectly assessed by quantifying mechanical work performed. When landing on rigid
36 ground, humans typically absorb much of the collision actively by bending their knees,
37 perhaps to avoid the discomfort of stiff-legged landings. We measured how work
38 performed by healthy adults ($N = 8$) changed as a function of surface cushioning for
39 drop landings (fixed at about 0.4 m) onto varying amounts of foam. Landing on more
40 foam dissipated more energy passively in the surface, thus reducing the net dissipation
41 required of subjects, due to relatively fixed landing energy. However, subjects actually
42 performed even less work in the dissipative collision, as well as in the subsequent
43 active, positive work to return to upright stance (approximately linear decrease of
44 about 1.52 J per 1 cm of foam thickness). As foam thickness increased, there was also
45 a corresponding reduction in center-of-mass vertical displacement after initial impact
46 by up to 43%. Humans appear to subjectively value cushioning, revealed by the extra

work they perform landing without it. Cushioning is thus worth more than the energy it dissipates, in an amount that indicates the subjective discomfort of stiff landings.

Introduction

Humans typically have a variety of choices for how to perform a motor task (Bernstein, 1967), yet often favor a particular strategy. That preference might be governed by one or more intrinsic factors, for example the desire to reduce mechanical work or metabolic energy demands on the body (Alexander, 1991; Cavagna and Kaneko, 1977; Elftman, 1966; Zarrugh et al., 1974). Other possibilities might be that people prefer to avoid discomfort, to gain stability, or to move faster, all of which might sacrifice economy. Some of these factors are subjective and difficult to quantify, making it challenging to characterize the factors governing movement. We propose a partial solution, which is to study intrinsic preferences based on their trade-offs against each other, and in particular against an objective measure such as mechanical work. Here we apply this approach to quantify the trade-offs of drop landings performed on cushioned and non-cushioned surfaces.

Drop landing entails absorption of the impact with the ground while controlling posture. Due to potential for pain or injury, impact forces are modulated by the landing strategy (Bressel and Cronin, 2005; Yu et al., 2006), for example by actively dissipating energy in the leg joints (McNitt-Gray et al., 2004; McNitt-Gray, 1993; McNitt-Gray, 2008; Zhang et al., 2000). The amount of active dissipation differs between males and females (Decker et al., 2003) and between amateur and professional gymnasts

(McNitt-Gray, 1993; Mills et al., 2009), suggesting that landing strategies can vary with task, individual, and training. This raises the question of how much active dissipation is appropriate, or whether it is needed at all. Active dissipation could largely be avoided by landing with relatively stiff and straight legs rather than allowing the knees or hips to bend, so that much of the fall energy would be absorbed passively by soft tissues such as cartilage, viscera, and fat (Zelik and Kuo, 2012). If an upright stance were ultimately desired, such a landing would also require few active adjustments to recover that position. However, the preference against stiff landings suggests disadvantages that make active dissipation favorable. For example, stiff landings might cause pain or discomfort, or make it more difficult to maintain balance upon ground contact. In contrast, softer landings would entail more active energy dissipation, which might allow the body to decelerate the body more slowly and less painfully. But soft landings presumably also have disadvantages. Not only would additional active negative work be performed for energy dissipation, but also positive work to raise the body center of mass (COM) to the eventual final posture. These respective trade-offs appear to favor a strategy lying between the extremes of stiffer and softer landings.

The costs associated with different strategies are, however, difficult to quantify. Most challenging are subjective costs such as discomfort, pain, instability, and other unanticipated factors, which are difficult to define, let alone quantify. Subjective costs might, however, be revealed indirectly through their trade-off against more objective

costs. Here many possible objectives might apply, including jerkiness of motion (Berret et al., 2011), torque production (Crowninshield and Brand, 1981), or sense of muscular effort (Prilutsky and Zatsiorsky, 2002). But in drop landings, the amount of energy to be dissipated is prescribed in the landing height, and so the corresponding work performed by the body is a particularly simple cost that is also straightforward to measure. As expected, more dissipative work is performed for greater drop heights (McNitt-Gray, 1993; Zelik and Kuo, 2012), and landing strategies are modulated as a function of surface cushioning (McNitt-Gray et al., 1994). The hypothesized trade-offs between costs suggest that less active work, and hence stiffer landings, would be preferred with increased surface cushioning.

Here we use the drop landing experimental paradigm to quantify the trade-off between surface cushioning and work performed by the body during landing. We tested whether surface cushioning would alter landing strategies and change the dissipative work performed by the body, in part because of the passive dissipation afforded by the surface. If so, then the change in active work relative to the change in surface cushioning could serve as a quantitative valuation of that cushioning and could thus serve as an objective alternative to subjective valuations. To quantify landing strategies, we performed an experiment measuring the mechanical work performed during drop landings onto varying thicknesses of foam (Fig. 1).

113 **Methods**

114 Eight healthy adult subjects participated in this study (6 male and 2 female, aged $21 \pm$
115 0.9 years, body mass 71 ± 15 kg, leg length 0.93 ± 0.056 m, mean $\pm$ standard
116 deviation). Each subject provided written informed consent according to Institutional
117 Review Board procedures.

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119 Trials consisted of drop landing onto zero to four layers of foam, each approximately 5
120 cm thick. The foam was overlaid on rigid, in-ground force plates (AMTI, Watertown, MA)
121 measuring vertical ground reaction forces (GRFs). Subjects first stood upright at the
122 edge of a raised platform, about 0.45 m above the force plates. They were instructed
123 to drop from their initial height, land as they preferred, and return to upright posture.
124 Subjects were instructed to cross their arms throughout each trial for consistency.
125 Eight drops were performed per condition, presented in random order.

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127 We estimated mechanical work performance during landing from the vertical ground
128 reaction forces (Fig. 2) (Cavagna, 1975). Forces were sampled at 1000 Hz and then
129 low-pass filtered with a third-order, zero-lag Butterworth filter with 25 Hz cutoff
130 frequency. The forces were used to estimate the COM acceleration, then integrated
131 twice to calculate vertical COM velocity and displacement, with an integration constant
132 determined to satisfy a final post-landing velocity of zero (Zelik and Kuo, 2012). The
133 net height change was determined from the net COM displacement from just before the
134 drop until completion of landing. Peak displacement was defined as the lowest COM

position reached during landing, relative to initial position. Finally, an Overshoot was calculated as the difference between the lowest COM position during landing and the final position. The COM work rate was calculated by taking the dot product of vertical GRF (under both feet) and COM velocity.

Negative and positive COM work was examined over the duration of landing. Landing consisted of a negative work phase termed Collision, followed by a positive work phase termed Recovery. The Collision work is defined as the negative work performed to bring the COM to zero vertical velocity. Recovery work is the positive work to raise the COM of the subject back to the upright resting posture. Recovery work close to zero, the theoretical minimal amount of positive landing work, would thus correspond to straight-legged landing, with theoretically no active work and only passive motion of the soft tissues within the body or of the foam (Zelik and Kuo, 2012). Landing was estimated to begin at touchdown, defined as when the vertical force increased above 1% of body weight, and to end when a moving average of the vertical work rate over 20 ms measured less than 30 W, or approximately 1% of peak work rates.

We attempted to maintain a consistent vertical drop height across subjects and conditions, despite varying amounts of static deformation of the foam. Foam deformation was evaluated by comparing standing heights as measured with a measuring tape before each foam thickness condition for each subject standing on the ground vs. on foam. We added wooden spacers atop the drop platform to compensate

for the difference in heights within about 0.010 m. Spacer thickness was about 0.030 – 0.035 m in the condition with greatest static deformation, 4 layers of foam. Drop height was subsequently estimated by dividing the sum of positive and negative COM work by the product of the subject's mass multiplied by the acceleration of gravity.

We also characterized the energy dissipation of the foam, which consisted of a polyurethane "memory foam" material. The work performed by foam was derived from ground reaction forces and the foam's kinematic displacement, estimated from practice trials performed with motion capture of markers on the toe (Fig. 3, left), which was treated as a proxy for foam deformation during contact. We estimated the mechanical work rate performed by the foam by multiplying the measured GRF by the foam deformation velocity in the vertical direction, and integrated over the landing duration to estimate the energy dissipated by foam. Assuming that the foam has negligible mass compared to the person, this yields a rough indicator of the foam's mechanical properties.

We compared subject COM kinetics and kinematics for each of the five landing conditions. The primary tests were to determine whether COM Overshoot, Collision, or Recovery work decreased with increasing foam. Collision work is negative and includes active and passive components, whereas Recovery work is positive and mainly active. We therefore used Recovery work as the primary indicator of both active dissipation and positive recovery, of equal amount but opposing sign. A significant change in

preferred landing strategy with amount of surface cushioning would be consistent with a subjective valuation of cushioning, in terms of the Recovery work saved per thickness of foam. To facilitate comparison between subjects of different sizes, measures were non-dimensionalized using base units of body mass m , leg length l , and gravitational acceleration g . All statistical tests were performed with dimensionless quantities. Some quantities were then re-dimensionalized for reporting purposes (in SI units). Statistical comparisons across the five conditions were performed with repeated measures analysis of variance (ANOVA), with post-hoc Holm-Sidak step-down correction for multiple comparisons where appropriate. In some cases, linear regression was used to describe trends as a function of foam thickness. The threshold for significance for all tests was set at $\alpha = 0.05$.

Results

Subjects were found to exhibit a number of systematic changes in their drop landing strategies, as a function of surface cushioning. The qualitative nature of these trends may be observed from the measured movement trajectories (Fig. 3), and are supported by quantitative tests, summarized below.

Subjects performed less mechanical work when landing on more cushioned surfaces (Fig. 3). For Recovery (positive) work, a decreasing linear trend was observed with more layers of foam (Fig. 4), equivalent to about -1.5 J per 1 cm of foam thickness (95% confidence interval, c.i., [-3.0, -0.03], $p = 0.046$). On average, subjects

performed 100.6 ± 46.7 J of Recovery work on bare-ground conditions, and 68.4 ± 20.2 J when landing on 4 layers of foam. Collision (negative) work magnitude also decreased with added foam (repeated measures ANOVA: $p = 0.0048$), with -386.4 ± 59.6 J of work on bare ground and -357.4 ± 33.2 J on four layers of foam during landing. Collision work did not, however, exhibit a linear trend with foam thickness (non-zero slope: $p = 0.11$). Furthermore, changes in positive or negative work did not appear to be attributable to variations in drop height (average 0.414 m, ranging 0.407 m to 0.426 m), which did not vary significantly across conditions (Fig. 4; repeated measures ANOVA: $p = 0.77$).

Subjects reduced COM Overshoot magnitudes when landing on greater amounts of cushioned foam (Fig. 3). We found average Overshoot of 0.148 ± 0.071 m on bare ground and 0.085 ± 0.040 m on 4 layers of foam, with an approximately linearly decreasing trend (Fig. 4; slope: -0.28 m Overshoot per m of foam thickness, 95% c.i., [-0.50, -0.06], $p = 0.015$). Although we observed substantial inter-subject variability, all trials resulted in non-zero Overshoot.

Peak forces generally decreased and the time to peak force increased with foam thickness (Fig. 3). Average peak forces changed significantly (repeated measures ANOVA: $p = 0.0087$), ranging 2678 N to 3172 N across conditions. This relationship did not appear to be linear (Fig. 4; non-zero slope, $p = 0.15$). Nevertheless, the time from touchdown until peak force did increase approximately linearly with added foam,

from 0.09 s to 0.16 s (slope: 0.39 s per m of foam thickness, 95% c.i., [0.26, 0.51], $p = 2.7 \times 10^{-7}$). In contrast, overall landing time from touchdown to upright posture did not significantly differ between conditions (repeated measures ANOVA: $p = 0.07$), and was, on average, 0.71 s.

Although subjects performed less work when landing on more foam, they varied considerably in the amount (Fig. 5). All subject-specific linear fits of recovery work vs. foam thickness had negative slopes (one-sample Student's t -test: $p = 0.019$), varying over a relatively large range, -4.4 to -0.4 J per cm of foam thickness. This is also illustrated by the difference in Recovery work between the most cushioned surface vs. bare ground, which ranged 3.2 to 83.9 J.

Discussion

We sought to test whether surface cushioning affects the mechanical work performed during drop landings. When landing on rigid ground, subjects actively performed negative Collision work to absorb energy, and then positive Recovery work to return to upright posture. With greater surface cushioning, subjects reduced the amount of negative and positive work, for example 30% less Recovery work for the most foam than without surface cushioning (Fig. 4). All subjects exhibited decreasing and approximately linear trends in Recovery work, albeit with different slopes (Fig. 5). Subjects appeared to take advantage of surface cushioning to reduce their own active energy absorption. The preferred movement strategy might depend on subjective and

qualitative factors, as well as a variety of unknown objective measures. However, their presence and subjective value might nevertheless be revealed, albeit indirectly, through their trade-offs against an objective quantity such as work.

The preferred landing strategy was not simply to maintain a constant amount of total energy dissipation, even though all of the landing conditions required the same amount of net work. Additional dissipation from surface cushioning could be expected to reduce the dissipation performed by the person, but the actual benefit was greater still: Subjects performed less work themselves and in total (human and foam) on more cushioned surfaces, by modulating the amount of active knee bending. Conversely, they performed the most work on the uncushioned surface, preferring to actively expend effort to dissipate a greater amount of energy. Surface cushioning therefore saves more than the energy it dissipates itself.

This strategy may be an indicator of a subjective preference to avoid pain, discomfort, or myriad other factors affecting movement strategy (Bressel and Cronin, 2005; Zelik and Kuo, 2012). It is not straightforward to measure or even define discomfort or pain, which have little direct relation to mechanical work. Still, some of the influence of non-work factors may be indirectly quantified in a repeatable way, through their trade-off against work. We anecdotally observed that the two subjects who performed the most active work on uncushioned ground, also had the greatest sensitivity (i.e. largest

reduction of Recovery work with more foam). This indicates subject-specific exchange rates between mechanical work and cushioning, which could vary with factors such as gender (Decker et al., 2003), skill level (McNitt-Gray, 1993), and pain tolerance. There are, of course other ways to measure an individual's valuation of cushioning, such as with quantitative measures (e.g., peak force, time to peak) and alternatives such a survey instruments (e.g., the Borg scale), or economic worth. Force measures are certainly indicative of factors associated with pain, although the actual relationship is unknown. Surveys may be helpful for determining a linguistic definition of preferences (e.g., differentiating between pain, discomfort, or other terms), but not for quantitatively predicting performance. Money could be used to incentivize landing stiffly or onto less-cushioned surfaces, with presumably higher payments required to incentivize more subjectively unpleasant tasks. We consider mechanical work to be a particularly simple metric, but additional measures would likely lend further insight.

These results may have implications for other tasks where collisions occur. During steady-state tasks such as walking, running, and hopping, positive and negative work must cancel over a stride. Although negative work may be returned in part by elastic tissues (Alexander, 1991), there are generally significant dissipative losses that must be offset by positive work from active muscle (Biewener and Roberts, 2000). Energy absorption by the environment might be expected to increase the losses and therefore the work demands, as is the case for locomotion on sand (Davies and Mackinnon, 2006). But our results suggest there may be cases where external energy dissipation

could actually help to reduce active energy absorption (and therefore positive work) by the human, and thus save metabolic energy or yield more subjective benefits. Indeed, some findings suggest that a cushioned surface can actually reduce the metabolic cost of running (Franz et al., 2012; Frederick et al., 1983; Tung et al., 2014). Cushioning also allows subjects to run with less knee flexion (Ferris et al., 1998; Ferris and Farley, 1997), which might reduce the mechanical work performed. It is also possible that the less economical gaits of older adults walking downhill (Hunter et al., 2010; Monsch et al., 2012) are adopted to enhance stability or avoid pain and discomfort. Extra dissipation is not usually considered helpful for locomotion, but it could potentially benefit humans both energetically and subjectively.

There are a number of limitations to this study. One is that we did not quantify specific contributions from lower-limb joints or segments, nor from soft tissue deformations, as has been performed previously (Devita and Skelly, 1992; McNitt-Gray, 1993; Pain and Challis, 2006; Yeow et al., 2009; Zelik and Kuo, 2012). We quantified work performed on the COM as a single and relatively simple indicator of the mechanics of landing, to indirectly quantify the trade-off or cost of avoiding discomfort. Mechanical work was chosen to capture energetic consequences of behavior throughout the entire drop landing, though it is only one of many potentially relevant energy and non-energetic measurements that may be relevant to subjects' movement strategies. It may also be helpful to also examine other measures such as individual joint contributions, peak

force, loading rate, kinematic jerk, or balance. Ultimately, mechanical work is only an indirect indicator of presumably multiple trade-offs.

Another limitation is that we did not test a variety of drop heights. We previously found Collision and Recovery work to increase in proportion to drop height onto an uncushioned surface (Zelik and Kuo, 2012). Combining that relationship with the present data, we would expect the active work of landing to be proportional to both height and the amount of foam or other cushioning. This might offer a relatively simple means to predict landing strategies for a variety of conditions, perhaps also adjusting for an individual's subjective sensitivity to cushioning. This possibility has yet to be explored.

In summary, we have quantified a trade-off between mechanical work and cushioning during drop landings. We found that the addition of energy dissipation via surface cushioning can actually reduce the negative and positive work performed by an individual. The sensitivity of that trade-off might also serve as an experimental means to quantify an individual's preferred movement strategy. It is also possible that trade-offs between subjective preferences, once quantified, could then be used to manipulate the preferred movement strategies. It can be difficult to quantify, or even define, preferences governing movement. However, indirect information about these preferences may be revealed by quantifiable metrics, with mechanical work as a particularly simple, scalar metric. This approach might potentially be used to quantify

332 trade-offs between subjective and objective motivations, with potential applications to
333 areas such as sports training and rehabilitation.

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Figure 1: Drop-landing protocol for estimating work performed when landing on different amounts of foam. Subjects initially stood upright (Stand) and then dropped about 0.4 m onto the foam landing surface (Drop). The landing was characterized by negative Collision work performed on the body center of mass (COM), and then positive Recovery work to return to upright. Ground reaction forces (GRFs) were used to calculate COM velocity $\vec{v}$ and displacement, as well as COM work. These were used to determine net and peak displacements in the vertical direction, as well as their difference, termed overshoot.

Figure 2: Representative trajectories for drop landings on (left column) Hard and (right column) Soft surfaces (0 and 4 layers of foam, respectively). (A.) Ground reaction forces (GRFs), (B.) vertical COM velocity, and (C.) vertical COM displacement. (D.) COM work rate was calculated from the dot product of COM force and COM velocity. (E.) Summary measures included negative Collision work and positive Recovery work, with their difference being the net work, equal to the potential energy of the drop. Negative work beyond the minimum required is equal to amount of Recovery work.

Figure 3: Time trajectories of kinematics and kinetics of the (left column) foam landing surface and (right column) combined human and foam landing surface ("human + foam"). (A.) Measured vertical ground reaction force vs. time for 0 – 4 foam layers. (B.) Vertical velocity and (C.) estimated position vs. time of the top surface of foam and human COM during landing. Position magnitude is relative to final position. (D.) Rate of work performed by foam or human + foam vs. time. Left inset compares rate of work between foam and combined system of human and foam. Right inset shows magnified view of positive work rate of human + foam. Trajectories for foam shown are representative data, for human + foam are average normalized trajectories across subjects. Grey arrows indicate the general trend as foam thickness increases.

Figure 4: Summary of force, displacement, and work measures for drop Landings on 0 – 4 layers of foam. (A.) Net drop displacement as estimated from the net work performed. (B.) Peak vertical ground reaction forces. (C) Landing duration and time to peak force after touchdown. (D.) The center of mass (COM) Overshoot, representing peak displacement beyond final upright position. (E.) Mean positive and negative work performed during landing. Positive work represents active work in Recovery to upright, negative work includes total Collision work for combined human and foam, shown along with (hatched bars) estimated contributions from foam. Statistically significant differences are indicated for overall repeated measures ANOVA (*), followed by post-hoc multiple comparisons using Holm-Sidak step-down procedure († with brackets indicating pairs), all with significance $p < 0.05$. There was no significant difference in net drop displacement and landing duration across conditions. Normalized quantities are shown in terms of base units of body mass m , leg length l , and gravitational acceleration g .

Figure 5: Recovery work for landing on different thicknesses of foam, specific to each subject ($N = 8$). Each data point represents average work performed for each condition, with subject-specific linear fits (solid lines). Recovery work represents positive work performed to return to upright position.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5