SOFT TISSUE MOVEMENT IN THE LOWER LIMB DURING DROP JUMPS

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Understanding loading on the human body and movement energetics is essential for researchers and practitioners to optimise training and investigate potential mechanisms of injury and adaptation. Recent work has suggested soft tissue movement relative to underlying bones during impact affects not only calculated loading but also metabolic cost. The aim of this study was to quantify the movement of the centre of mass of the soft tissues of the shank during high-impact, drop jump landings from 30 and 45 cm in healthy, adult males, and quantify the work done by these tissues. Soft tissue centre of mass moved by up to 0.038 m in the vertical direction (average: 0.021 m), and the soft tissues performed 2.9-3.5 J of work (4.1-6.4 J absolute work) during the landings. These results may hence have a significant effect on calculated joint torques and movement energetics.

KEYWORDS: movement energetics, inverse dynamics, force dissipation, plyometrics, lower limb

INTRODUCTION: A key application of biomechanics in sport is understanding loading and movement energetics during performance of dynamic tasks, to inform potential training effects and potential mechanisms of injury. Plyometric training is commonly used by strength and conditioning professionals, with drop jumps commonly used to both assess and enhance neuromuscular control of the lower limb. It is also commonly used by researchers to replicate the typical scenario in which non-contact anterior cruciate ligament injuries occur.

To quantify loading during dynamic tasks such as the drop jump, inverse dynamics analyses are typically used. However, an inherent assumption in these calculations is the rigidity of the human body, despite the obvious presence of soft tissues that do not maintain a rigid structure during impacts. High-speed footage has repeatedly shown large movements of these soft tissues, complicating mechanical analyses by highlighting the limitation of the assumption of rigidity and immobility. Inclusion of these 'wobbling masses' in simulation studies of landings has been shown to both improve the ability of a model to accurately represent measured force profiles and reduce calculated joint torques (Gittoes et al., 2006; Pain and Challis, 2006). Recent experimental work (e.g. Riddick and Kuo, 2016) supports the important role the soft tissues may play in passive force dissipation during dynamic tasks, which further complicates the accurate determination of mechanical work and the relationship with metabolic energy expenditure.

In a dynamic, high-impact situation such as plyometric training, the magnitude of forces exerted and rate of loading are higher than those observed in walking or running, which is likely to influence the calculated work of the soft tissues. Despite its importance in understanding and optimising training effectiveness, it is unknown how much mechanical energy is dissipated by the tissues during performance of the drop jump. To establish this requires knowledge of the movement of the segment centre of mass (COM) during the task which is, in itself, experimentally challenging. The aim of this study was to experimentally determine the movement of the COM of the soft tissues of the shank during high-impact, drop jump landings and quantify the work done by these soft tissues during this task. Quantifying these variables has significant implications for understanding the mechanical and metabolic processes underpinning effective performance of this task, in addition to investigating the appropriateness of assumptions underpinning inverse dynamics analyses.

METHODS: Participants: Following university ethical approval and written informed consent, four healthy, recreationally active males (age: 34.7 ± 7.2 years, height: 1.76 ±

0.09 m, mass: 82.0 ± 6.4 kg) participated in this study. All were injury free for the preceding 3 months, did not have a history of lower limb surgery and were familiar with performance of the drop jump task. Participants were advised to refrain from unaccustomed strenuous activity for the 24 hours preceding data collection.

Motion analysis: A total of 56 retro-reflective, passive 6.4 mm diameter markers were attached around the shank segment of the right limb (also the preferred jumping limb for all subjects), in a 7 x 8 array using standard double-sided adhesive tape. Additional markers were attached to the medial and lateral malleoli and femoral condyles. The shank was defined as the segment between the lateral knee joint centre and lateral malleolus (average length: 0.44 m, standard deviation: 0.023 m), and the markers covered the proximal 15 to 75% of this total length. Rows and columns were spaced equally around the segment and all trials were completed barefoot. Marker position in 3D space was determined using a 16 camera high-speed motion analysis system (750 Hz, Vicon T20 and T20S, Oxford Metrics PLC., Oxford, UK), with force data acquired using two force plates positioned side-by-side (1000 Hz, Kistler 9281E, Kistler Group, Winterthur, Switzerland). Pilot analysis showed this camera set-up to be a valid, accurate method of acquiring data at the very high sample rates necessary to capture soft tissue movement during impact. Use of an array of small markers is a valid method of quantifying the movement of the underlying soft tissues over a limb segment as the markers have minimal mass and the skin has a low stiffness, so their movement reflects to a large extent the motion of underlying tissue when the impact is distant from the marker. Arrays also represent the movement of a segment as a whole, as they are less susceptible to spikes in data sometimes observed when markers are used in isolation or pairs. Across trials, measurement of the linear distance between two markers using this protocol has been shown to deviate by a maximum of 0.21 ± 0.073 mm for fast movement trials at 750 Hz when fixed to solid 3D objects comparable in size to a forearm, shank and thigh during fast dynamic movements. Root mean square difference between average linear distances and sector areas obtained in two separate trials were negligible (maximum of 0.59% and 0.82% of trial average respectively). Subjects were instructed to step from 30 and 45 cm boxes with the test limb keeping their hands on their hips, jump as high as possible after spending as little time as possible in contact with the ground, and land on the two plates as they usually would. Two trials were obtained from each subject in each condition, and analysis focused on the landing to jump phase (i.e., first landing) from approximately 25 ms prior to impact to 225 ms after impact.

Data analysis: All data was reconstructed and labelled using Nexus 1.8.5 (Oxford Metrics PLC, Oxford, UK), with incomplete marker trajectories of up to 10 frames long reconstructed using the quintic spline gap filling procedure. All further post-processing was completed using custom-written Matlab code (MathWorks, Natick, MA., USA). Data was filtered using a fourth order, zero-lag, low-pass filter at 60 Hz, established using residual analysis (Winter, 2005) on a sample of twelve representative trials from three subjects.

Delaunay triangulation was used to fit multiple tetrahedrons to the surface marker array. Assuming uniform density, the mass of the shank segment enclosed by the marker array was calculated by summing the individual tetrahedron volumes. The mass of the soft tissues was based on the data used by Pain and Challis (2006), which calculated the soft tissues to account for 67.5% of total shank mass. The weighted COM of the array was subsequently calculated from the mass of each tetrahedron. Inverse kinematics were used to establish the knee and ankle joint centres during static and dynamic tasks and reduce the likelihood of erroneous spikes in calculated shank lengths due to individual anatomical landmark movement. These joint centres were used to define shank length. The location of the rigid segment COM was subsequently calculated as 44.59% of this shank length based on the findings of de Leva (1996), a more valid dataset than that of Dempster (1955) for use with the athletic population of interest.

Due to the multidirectional nature of soft tissue movement during impact, force of the soft tissues during impact was calculated as the product of soft tissue mass and resultant acceleration of the soft tissue COM. Soft tissue power was calculated as the product of soft tissue force and resultant velocity of the COM of the soft tissues relative to the rigid segment COM, and soft tissue work as the time integral of power. To quantify the total work done (regardless of directionality), absolute power and work were also calculated using absolute force and absolute velocity data. To investigate the potential effect of this movement on the assumption of a fixed COM for inverse dynamics, the position of the COM relative to the proximal segment end (the knee joint centre) was also calculated as a percentage of total shank length as determined using the inverse kinematics data. To identify where the majority of soft tissue movement occurred and hence potentially the area of greatest energy dissipation, the shank markers were used to create 48 sectors. Sector area was calculated using three-dimensional co-ordinates to account for movement of the soft tissues along all three axes. Changes in area and location were calculated relative to those established during a 2 s static trial prior to dynamic testing.

All statistical analysis was completed in SPSS (IBM SPSS Statistics 22, IBM Corp., Armonk, NY., USA). As the data satisfied the assumptions of normality (assessed using Shapiro-Wilk's test) and sphericity (Mauchly's test), between-height differences were assessed using a univariate analysis of variance with significance set at $p < 0.05$. Effect sizes were calculated using Cohen's d and interpreted using the scale of Hopkins (2006), i.e. <0.6 = small, <1.20 = medium, 1.20 and above = large.

RESULTS: Peak ground reaction forces during jumps from 30 cm were 2022 ± 622.2 N (2.57 ± 0.99 bodyweights) and 2317 ± 801.8 N (2.94 ± 1.22 bodyweights) from 45 cm. Large amounts of soft tissue movement were observed, with a distinct movement in the position of the COM of the soft tissues relative to the fixed position typically used in inverse dynamics analyses. Group average absolute movement of the soft tissue COM relative to the rigid segment COM across the entire impact, accounting for resting differences in the anteroposterior, mediolateral and vertical directions were 0.008, 0.007 and 0.021 m at 30 cm, and 0.010, 0.005 and 0.020 m at 45 cm. Maximum absolute differences across the group were 0.016, 0.013 and 0.030 m from 30 cm, and 0.033, 0.016 and 0.038 m from 45 cm. COM position as a percentage of shank length subsequently varied by 5.2 ± 4.01% and 6.0 ± 3.12% from the 30 and 45 cm heights respectively.

This movement resulted in notable amounts of work being done by the soft tissues, with 2.9 ± 1.48 J of work and 4.1 ± 1.55 J of absolute work performed by the tissues during landing from 30 cm. At 45 cm, these values were 3.5 ± 3.30 J and 6.4 ± 4.21 J respectively. Between-height differences in force, work done and absolute work done were not statistically significant, but differences in absolute work (55%) were of medium effect size. The largest change in sector area was at the proximal posterior shank, where total changes of 16.1% and 15.4% were observed during the 30 and 45 cm jumps (Table 1).

Table 1. Total percentage changes in shank sector area at proximal and distal shank relative to static, resting area during initial drop jump landings from 30 cm and 45 cm

Height	Shank position	Lateral	Anterior	Medial	Posterior
30 cm	Proximal	9.6	12.2	13.3	16.1
	Distal	3.8	4.2	5.7	4.9
45 cm	Proximal	5.6	9	11.9	15.4
	Distal	4.4	5.9	5.4	5.7

DISCUSSION: The aim of this study was to experimentally determine the movement of the COM of the soft tissues of the shank during high-impact, drop jump landings and quantify the work done by these soft tissues. The results show marked movements of the soft tissue COM of relative to the rigid segment COM of up to 0.033, 0.016 and 0.038 m in the anteroposterior, mediolateral and vertical directions during the initial landing from a drop jump. An average of 2.9 and 3.5 J of work and 4.1 and 6.4 J of absolute work were performed by the soft tissues of the shank during landing from the two heights, with both of these findings having important implications for both researchers and practitioners in understanding the energetics and loading of the lower limb during this particular task.

High-speed video footage has previously shown movement of the soft tissues relative to the underlying bone during impact, altering the instantaneous shape of the segment. The largest changes in sector area of 15-16% were seen at the proximal posterior shank where the soft tissue:bone ratio is highest in the segment; energy is most likely to be dissipated here as force is transmitted more effectively along rigid tissues such as bone. This movement significantly altered the position of the COM, which may potentially affect calculated joint torques calculated using a rigid body assumption.

To the authors' knowledge, this study is one of the first experimental studies to quantify soft tissue movement relative to previously published rigid segment centres of mass and calculate the work done by the soft tissues during drop jumps. Values observed are slightly lower than the 7.3 and 2.6 J average work done reported by Schmitt and Gunther (2011) for energy dissipated by the shank in the vertical and horizontal directions during running, which may be due to the different methods used to both acquire the data (2D, single subject) and calculate mechanical work done. The marker array used in this study covered the 60% of the shank segment where most soft tissue movement is likely, so it is possible the results of this study may underestimate the work done. As the soft tissues of the thigh also perform additional work, observed values here would fit better with the 13 J of work done by the entire lower limb reported of Zelik and Kuo (2010), which calculated work done as the difference between measured joint work and work performed on the whole body COM.

The calculated work of the soft tissues shows that the movement of these tissues has a function, reducing the influence of impact on the body in a passive manner. Differences between heights were small. The increase in work done may be due to increased velocity of the tissues during landing from the higher height, but the interaction between altered muscle activation (and subsequently, muscle's role as an energy transmitter or dissipater) and work requires further investigation. Developing our understanding of how this work changes during different training exercises could improve our understanding of the demands on the tissues and the body during activity, and enhance design and selection of training exercises.

CONCLUSIONS: Large soft tissue movements occur during the initial landing from a drop jump, which alters the position of the COM of the segment and performs work. These results have important implications for researchers and practitioners using inverse dynamics analyses and quantifying training load, as these movements in the soft tissues may change calculated joint torques and alter the metabolic cost of task performance.

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