THE INFLUENCE OF MASS PROPORTIONS AND COUPLING STIFFNESS ON LOADING IN SIMULATED FOREFOOT-HEEL LANDINGS

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The aim of this study was to gain a further insight into whole body mass proportion and coupling stiffness contributions to loading in forefoot-heel landings. Two landing performances were simulated using a customised wobbling mass model. Personalised segmental mass proportions and coupling stiffness values were independently and simultaneously modified in the model and the impact loads examined. A 10% larger rigid mass proportion increased the peak GFz and ankle moment by 0.73 BW and 0.38 $N \cdot m.kg^{-1}$, respectively. Reducing mass coupling stiffness had a smaller influence on loading than mass proportion and alleviated the larger peak GFz produced with relatively larger rigid mass proportions. A neuromuscular response that is tuned to an individual's inherent mass properties may help to alleviate the excessive loads incurred in landing.

KEY WORDS: Impacts, Wobbling Mass, Rigid Mass, Lower Extremity

INTRODUCTION:

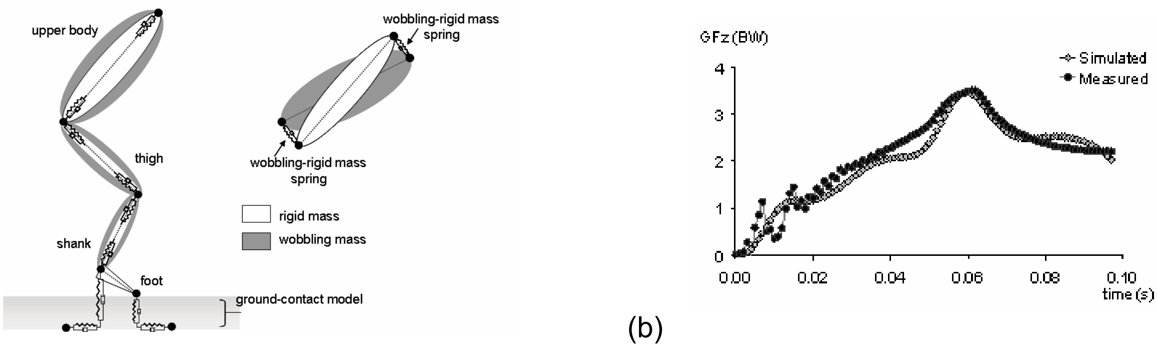
The rapid and large forces experienced during impacts performed in sports, such as dismounting in gymnastic routines, have been associated with a high potential for lower extremity injury (McNitt-Gray, 1991). Humans possess several mechanisms that can influence or modify the challenging forces experienced during impacts. Nigg and Liu (1999) highlighted that changing the geometric position of the lower extremity joints and the coupling between soft (wobbling) and rigid masses can influence the forces experienced during heel-toe running. Liu and Nigg (2000) later suggested that without alterations to wobbling and rigid mass coupling properties, lower body mass and mass distribution have important effects on loading during running impacts. Pain and Challis (2004) recently confirmed that increasing the ratio of bone mass relative to soft tissue mass in the body by 20% produced a notable 13% increase in the peak impact force experienced during a simulated heel drop landing while modifying the stiffness between wobbling and rigid masses had less effect on the forces produced.

Investigations examining the independent contributions of mass proportions and coupling modifications to impact loading have provided a valuable insight into load attenuation mechanisms used in heel-ground impacts. In contrast, a limited understanding of the role of inherent mass properties and modifiable coupling properties in attenuating the challenging forces produced in commonly performed forefoot-heel landings has been achieved. Furthermore, Liu and Nigg (2000) suggested that body mass distribution might strongly couple with neuromuscular control, which is partially responsible for mass coupling properties, to influence impact loading. Examination of the effects of simultaneously modifying mass distribution and coupling on impact loading in forefoot-heel landings has the potential to enhance understanding of the mechanical factors influencing load attenuation during potentially injurious sports movements. This investigation aimed to examine the influence of whole body mass proportion on impact loading in forefoot-heel landings and to investigate the contribution of simultaneously modifying mass proportions and coupling stiffness to load attenuation.

METHODS:

Model development: A four-segment, planar simulation model of landing (Gittoes, Brewin and Kerwin, 2006), was developed using the dynamics simulation package AUTOLEV™3.4 (Online Dynamics, Inc.,USA). The foot segment comprised a single rigid mass and was coupled to the ground using four spring-damper systems that represented the vertical (GFz) and horizontal (GFy) ground reaction forces produced at the forefoot and heel. As illustrated in Figure. 1a, the shank, thigh and upper body segments each constituted a wobbling and rigid mass that were connected using two spring-damper systems located at the distal and proximal end of each respective segment. A Runge-Kutta numerical integration algorithm was used to advance the solutions for the differential equations of motion.

Model inputs: Initial conditions and joint angle time histories taken from two drop landing trials (height 0.46m) performed by a female subject (age: 22 years, mass: 69.0 kg) were used to start and drive the simulation model. Ethical approval and written informed consent for the data collection session was obtained prior to the onset of the study. A Cartesian Optoelectronic Dynamic Anthropometer (CODA 6.30B-CX1) motion analysis system was used to obtain coordinate data for the right metatarsophalangeal (mtp), ankle, knee, hip and shoulder joint centres (sample rate: 200 Hz) and a Kistler 9287BA force plate was used to acquire (sample rate: 1000 Hz) synchronised GFz and GFy data for each landing performance. Smooth foot orientation and joint angle time histories and their first two derivatives were derived using the two dimensional joint centre coordinate data and a quintic spline routine (Wood & Jennings, 1979). Trial-specific foot orientation and angular velocity and whole body mass centre motion at first ground contact, which was defined using the GFz data, initiated the simulated motion. Joint angle time histories were used to drive the model for the impact phase duration. Completion of the impact phase was established as the time at which the measured GFz first reached a minimum following peak GFz production.



(a) (b)

Figure 1: (a) The four-segment wobbling mass simulation model. Segmental wobbling and rigid masses were coupled using two spring-damper systems. (b) Simulated and measured GFz time histories for an evaluated landing trial (Performance B).

Anthropometric measurements were taken from the subject and combined with a component inertia model (Gittoes & Kerwin, 2006) to derive segment-specific wobbling and rigid mass inertia parameters for the modelled segments. Mass coupling and ground contact spring parameters were derived using an optimisation procedure that aimed to minimise the difference between the simulated and actual landing performance GFz and GFy time histories. A simulated annealing algorithm (Goffe, Ferrier & Rogers, 1994) was used to vary the spring parameters in the optimisation procedure. Realistic initial values and boundaries for the mass coupling spring parameters were derived using a stamping movement protocol similar to that described by Pain & Challis (2006). Penalties were imposed in the optimisation procedure to ensure that the resulting simulated wobbling mass motion and foot deformations were realistic.

Model evaluation & application: The accuracy of the simulation model in replicating the loads experienced in the actual landing performances is illustrated in Figure 1b and was assessed by quantifying the level of agreement between the evaluated (simulated) and measured ground reaction force profiles. When expressed as a percentage of the measured force range, the root mean squared differences between the simulated and measured GFz were 9.0 % and 10.8 %, respectively for the two landing performances. The model reasonably replicated the measured peak GFz and time of peak GFz to within 8.5 % and 9 ms, respectively. Following model evaluation, the subject-specific mass proportions used in the evaluated motion were modified such that the percentage of rigid mass relative to wobbling mass in the shank, thigh and upper body segments were simultaneously modified by 2.5% perturbations within the range of 0% to 10% of the segment mass. Total segmental masses remained constant for each simulation performed. Simulations were also produced using the modified mass proportions accompanied by simultaneous changes (± 5% of the optimised solutions) to the shank, thigh and upper body mass coupling stiffness values. The simulated motion was reproduced with each perturbation and the impact loads produced in the evaluated and modified simulated motions were compared. A positive perturbation in the mass proportion and coupling stiffness produced a larger proportion of rigid mass in the whole body and an increase in stiffness between wobbling and rigid masses, respectively.

RESULTS:

Similar changes in peak GFz were produced in each performance as a result of modifying rigid mass proportion and coupling stiffness (Figure 2). Increasing rigid mass proportion typically increased the peak GFz when negating or incurring mass coupling stiffness changes. Without mass coupling adjustments, a 0.73 BW (performance B) increase in peak GFz was produced by modifying the rigid mass proportion by 10%. Simultaneously increasing mass coupling stiffness further inhibited GFz attenuation by increasing peak GFz with each rise in rigid mass proportion. In contrast, reducing mass coupling stiffness alleviated the increased peak GFz associated with larger rigid mass proportions. Modifying the rigid mass proportion inhibited peak GFz attenuation more than modifying the mass coupling stiffness. A 5% increase in rigid mass proportion increased peak GFz by as much as 0.21 BW (performance A) while the largest increase in peak GFz produced by increasing the mass coupling stiffness was 0.06 BW for the same landing and mass proportion.

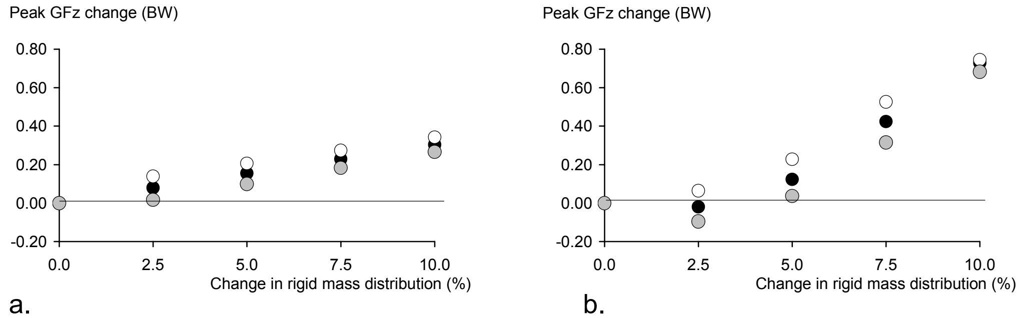


Figure 2: Influence of mass distribution and mass coupling stiffness on the magnitude of the peak GFz experienced in simulated landings performances A (a) and B (b). ● = 0 % change in stiffness, ○ = 5% change in stiffness, ◍ = -5% change in stiffness.

Independently increasing the rigid mass proportion typically increased the peak net ankle and knee moment produced in each performance. A 10% increase in rigid mass proportion slightly increased the peak net ankle moment by 0.38 $N \cdot m.kg^{-1}$ (performance A) and excessively increased the peak net knee moment by as much as 3.5 $N \cdot m.kg^{-1}$ (performance B). Simultaneous reductions in the mass coupling stiffness helped to alleviate the increased ankle joint loading produced with the 10% increase in rigid mass proportion at the ankle. Compared to the ankle, relatively larger changes in knee joint loading were produced as a consequence of simultaneous mass coupling stiffness alterations in each performance.

DISCUSSION:

The contribution of mass proportions and coupling stiffness to impact loading in forefoot-heel drop landings were examined. When mass coupling stiffness, which can be altered by muscle activity (Nigg & Liu, 1999), was maintained between the simulated landings, larger rigid mass proportions heightened external and joint loading. Previous studies have similarly reported increases in peak GFz in running impacts (Liu & Nigg, 2000) and heel drop landings (Pain & Challis, 2004) with increased rigid mass proportions. The landing technique, which was defined by the joint angle time histories used in the simulation model, was maintained between simulated landings. The increased impact loads incurred with larger rigid mass proportions may therefore be a consequence of a maintained vertical rigid whole body mass centre acceleration accompanied by progressively increased magnitudes of rigid mass.

This study confirmed the suggestion of Liu and Nigg, (2000) that mass distribution (proportion) coupled with a neuromuscular response, which contributes to mass coupling properties may influence the forces experienced in impacts. Increasing the coupling stiffness between wobbling and rigid masses heightened the increases in peak GFz and joint loading produced in the investigated landings performed with increased rigid mass proportions. An individual may therefore be predisposed to excessive loading in forefoot-heel landings due to inherently large rigid to wobbling mass proportions coupled with a neuromuscular response that incurs high muscle tension upon impact with the ground.

Without mass distribution changes, increases in mass coupling stiffness have been found to have a small effect on the peak GFz produced in contrasting heel impacts (Nigg & Liu, 1999; Pain & Challis, 2004). Modifying mass coupling stiffness in the forefoot-heel landings typically had less influence on external and joint loading than modifying mass proportions, which suggested that increased wobbling mass motion incurred by reduced coupling stiffness may not fully compensate for large rigid mass contributions to vertical impact loading in the first 100 ms of landing. The greater sensitivity of peak GFz and joints moments to mass proportion changes compared to coupling stiffness suggested that simulation models of landing ideally require the use of subject-specific mass proportions and accurate coupling properties may be less critical for producing realistic simulations. Future investigations aim to examine the contributions of mass proportions and coupling stiffness and damping properties of individual segments to impact loading in forefoot-heel landings, which may provide further insight into the factors influencing loading in potentially injurious landings performed in sport.

CONCLUSION:

A simulation model of landing was used to examine the influence of mass proportions and coupling properties on loading in forefoot-heel landings. The inherent mass proportions of sports performers had the potential to influence loading more than mass coupling stiffness in potentially injurious forefoot-heel landings. Reducing mass coupling stiffness, which may be achieved by developing a modified neuromuscular response in training, may help to alleviate the excessive impact loads incurred due to an individual's inherent mass proportions.

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