EVALUATION OF A WOBBLING MASS MODEL SIMULATING FEMALE IMPACT LANDINGS

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Females involved in sport are more susceptible to injury during landing than their male counterparts, which may partially be attributed to their ability to attenuate the excessive loads experienced. This investigation aimed to evaluate a customised simulation model developed to replicate the kinetics of female impact landings. The model incorporated a rigid foot and shank, thigh and upper body segments, which each comprised wobbling and rigid masses. Model accuracy was defined by quantifying the differences between simulated and actual landings. The model reproduced ground reaction force profiles to 16% of the measured range and peak vertical force times to 8ms. The limitations of using a rigid foot were addressed and future applications of the model for gaining insight into load attenuation strategies used by females in landing were discussed.

KEY WORDS: Optimisation, Foot segment, Loading, Injuries

INTRODUCTION: In 1995, a review by the National College Athletic Association highlighted that females involved in sport were two to eight times more likely to sustain a knee injury that their male counterparts (Arendt & Dick, 1995). Landings, such as those performed when dismounting from apparatus in gymnastics or landing from a jump in basketball have been linked to a high number of the sustained injuries (Moeller & Lamb, 1997). The ability of the female to effectively dissipate the loads experienced has been questioned (Decker, Torry, Wyland, Sterett & Steadman, 2003) and may explain their susceptibility to injury in landing.
A model, which appropriately considers the mechanical properties of the female is necessary to provide a thorough insight into the loads incurred in landing. Wobbling mass models have been used to investigate the kinetics of dynamics movements (Gruber, Ruder, Denoth & Schneider, 1998). However, these previous wobbling mass models of landing have not included the foot segment, which omits a potentially fundamental contributor to load attenuation during this phase. In addition, reporting of the level of accuracy achieved by wobbling mass models in replicating the kinetics of landing has previously been limited or has been restricted to a single landing movement performed by one subject. Thorough model evaluations are necessary to ensure appropriate simplifying assumptions are made by a model and, as highlighted by Yeadon & King (2002), are essential in determining whether the model predictions have relevance to the system of interest.
Successful, quantitative evaluations of simulation models have been achieved by determining the levels of agreement between kinematic and kinetic indicators of corresponding simulated and actual performances (Brewin, Yeadon & Kerwin, 2000). Comparisons of kinematic indicators of performance have been considered appropriate for evaluating models used to investigate technique and performance. Conversely, models used to investigate loading should primarily be evaluated by comparing kinetic indicators (Yeadon & King, 2002). The aims of this investigation were to develop and conduct a kinetic evaluation of a simulation model of females performing landings and to determine the appropriateness of the model for gaining a realistic insight into impact loading. The customised simulation model included wobbling and rigid masses and additionally incorporated a rigid foot segment.

METHODS:
Simulation model: The equations of motion for the planar four-segment wobbling mass model were generated in the dynamic simulation package, AUTOLEV™3.4 (Online Dynamics, Inc., USA). The model (Figure 1) comprised a rigid foot together with shank, thigh and upper body segments, which each consisted of wobbling and rigid masses. In each segment, two

linear damped springs connected a wobbling mass to the corresponding rigid mass. The simulation model included a ground contact model comprising four non-linear, spring-damper systems: a vertical and horizontal system located at the forefoot and heel. A Runge-Kutta numerical integration algorithm, comprising variable step-length, was used to advance the solutions of the model's differential equations of motion.

The simulated motion was initiated using the initial foot orientation and angular velocity and the initial wobbling mass configurations and their first two derivatives. The vertical and horizontal mass centre velocities at impact were also required as input into the model. The simulation model was driven using ankle, knee and hip joint angle time histories. The modelled outputs included forefoot, heel and combined vertical and horizontal ground reaction forces, net joint moments and the motion of the whole body and wobbling masses.

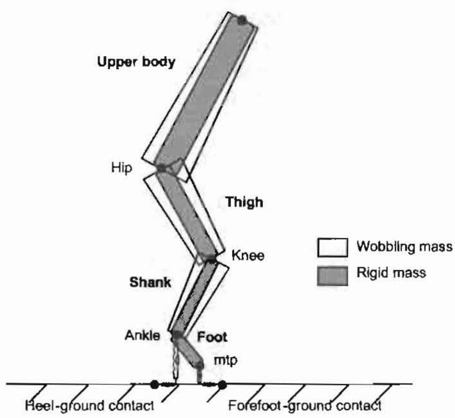

Figure 1 The four-segment wobbling mass model.

Data collection and processing: Two females (age 24 & 22 years, mass: 56.8 & 69.0 kg) each performed four drop landings from heights of 0.46 m, 0.61 m and 0.82 m. The South West Local Research Ethics Committee gave approval for the data collection session and the subjects provided written informed consent. Anthropometric data were collected on each subject according to the measurements detailed for the mathematical inertia model of Yeadon (1990) and were used as input into a component inertia model (Gittoes & Kerwin, 2004) to derive personalised inertia parameters.

Active markers were located on the metatarsophalangeal (mtp), ankle, knee, hip and shoulder joint centre of each subject and were automatically tracked by a CODA motion analysis system (6.30B-CX1) at a rate of 200 Hz for a 5 s capture period during each landing. Coordinate data were used to define foot orientations and joint angle configurations. Smoothed continuous time histories and first and second derivatives for the foot orientation and joint angles were obtained for the duration of each landing trial using a quintic spline routine (Wood & Jennings, 1979).

Synchronised ground reaction force data were measured using a Kistler 9287BA force plate at a rate of 1000 Hz for a 5 s capture period. The impact phase onset of each landing was defined as the instant of first ground contact. Mass centre velocity changes were calculated from the ground reaction force data using the trapezoid rule for integration. The duration between the impact phase onset and the instant at which the mass centre vertical velocity first reached zero defined the impact phase of each landing.

Model evaluation: The model accuracy was evaluated by comparing the impact phase of corresponding simulated and actual landing performances for three trials performed by each subject across the range of landing heights. Initial foot orientation, angular velocity and mass centre velocity at impact were taken from the actual performance to initiate the simulated motion. Joint angle time histories of the actual performance were used to drive the model.

A simulated annealing algorithm (Goffe, Ferrier & Rogers, 1994) was used in an optimisation procedure employed to obtain appropriate estimates for all modelled spring parameters.

Initial estimates and boundaries for the wobbling mass parameters were defined using stiffness and damping parameters derived experimentally. An objective function comprising a weighted summation of the root mean squared (RMS) differences between simulated and actual vertical and horizontal ground reaction forces was developed. The weighting was based on the mean ratio of the ranges in the vertical and horizontal ground reaction forces, which were determined from the four experimental landing trials performed at each height. Minimisation of the objective function was considered achievable, only if the modelled spring properties reflected the mass coupling and ground contact stiffness and damping properties of the actual landing. The level of agreement between the optimised, simulated landing and the actual performance was subsequently used to indicate the simulation model's accuracy.

RESULTS: A reasonable level of agreement was achieved between the simulated and measured ground reaction forces, as illustrated in the example force profiles provided in Figure 2. Expressed as a percentage of the actual force excursions, the mean and standard deviation of the RMS difference between the simulated and measured vertical and horizontal ground reaction forces was 14.6% (SD:2.5%) and 17.5% (SD:2.2%), respectively across the six evaluated trials. The model also typically reproduced the foot contact strategies used in the actual landing performances. A reasonable replication of the peak loading characteristics was achieved by the simulation model. The mean percentage difference between the simulated and measured maximum GFz was 20.1%. The model was less successful at replicating the magnitude of the maximum GFy. However, the model successfully reproduced the temporal GFz and GFy characteristics. The mean difference between the simulated and measured time to maximum GFz was 8 ms. Similarly, a 7ms difference in the simulated and measured time to the first peak in the GFy profile was achieved.

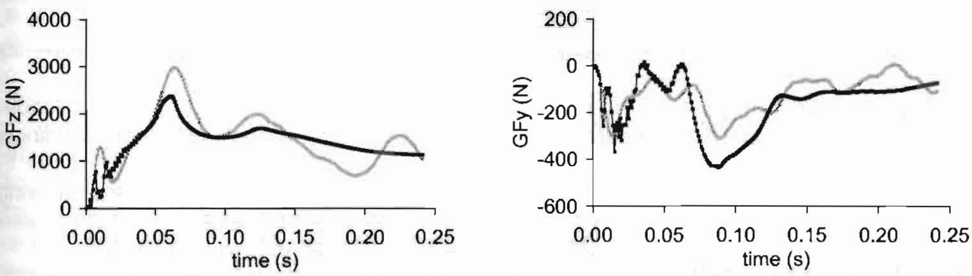

Figure 2 Simulated (grey) and measured (black) vertical (GFz) and horizontal (GFy) ground reaction forces for a trial performed by one subject from the 0.46 m landing height.

DISCUSSION: A wobbling mass model, which incorporated a rigid foot segment was presented and evaluated. The model replicated the force profiles of actual landings, performed from a range of drop heights, to 16% of the measured values. The model produced a less accurate replication of the magnitude of the peak impact forces but was particularly successful in replicating the temporal characteristics of the peak forces. The difficulty in replicating forces using a wobbling mass model comprising a one-segment foot for lower velocity impacts than investigated in this study was recently highlighted by Wilson (2003). The discrepancy observed between the simulated and measured forces may partially be explained by the inclusion of a rigid foot segment, which omits the load attenuation properties of the elastic structures of the foot. As the foot deforms during impact with the ground, the ligaments and tendons stretch to absorb some of the shock and the impulse is a more sustained force of smaller amplitude (Salathé JR, Arangio & Salathé, 1990). The presented model neglected these mechanical properties of the foot. The simulated forces were therefore not attenuated as successfully as the forces in the actual landing. The foot segment inclusion was however, considered primary in the successful replication of the temporal characteristics of the forces. The foot segment lever action potentially caused the impact force to occur later than if a heel only impact had been assumed. The rapid occurrence of the impact force peak has been reflected in previous applications of models that have ignored the foot segment (Cole et al., 1996). The effects of including the foot segment may be examined directly in the future by comparing the kinetics produced using a four-segment and corresponding three-segment model. Future developments of the model should focus on the inclusion of a non-rigid foot to more successfully replicate the kinetics of landing. However, the presented model has been successfully applied to gain insights into load attenuation strategies used by females in landing. For example, the influence of modifying mass coupling properties on the impact loads experienced in drop-landing was recently investigated using the model (Gittoes, Kerwin & Brewin, 2004).

CONCLUSION: A customised wobbling mass model of females performing impact landings was presented. The model evaluation highlighted that a reasonable replication of the kinetics of drop-landings performed from a range of heights was achieved. In particular, the inclusion of the foot segment was suggested to be responsible for the successful replication of the temporal characteristics of the forces. This highlights the potential benefits gained from including a foot segment in future developments of simulation models of landing. The model may be applied to gain insights into the development of more effective landing techniques, which can subsequently be used to reduce the risk of injury in potentially injurious landings.

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