PREDICTING GROUND REACTIONS DURING SINGLE-LEG LANDINGS USING ZERO-MOMENT POINT

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INTRODUCTION

Anterior cruciate ligament (ACL) injuries affect approximately 1 in 3,000 individuals each year [1] and most occur during non-contact sport movements, such as sidestepping or single-leg landing [2]. Injury prevention aims to modify body position to minimize knee loads during weight-acceptance phase of these movements [3, 4].

To determine optimal whole-body kinematics for minimizing ACL injury risk, accurate ground reactions are necessary to calculate muscle and joint loads. Directly measuring ground reaction forces is not practical when investigating emergent behaviors modifying neuromuscular control or joint-level movement for reducing loads. Several computational approaches can predict ground reactions from body kinematics [5]. One approach deserving further exploration is predicting ground reactions by locating the ***Zero-Moment Point*** (**ZMP**) [5, 6], a well-known notion within the robotics field. For biomechanists, the ZMP is conceptually similar to the Center of Pressure (CoP), but the ZMP uses gravity and inertia forces rather than contact (reaction) forces and moments. The ZMP and CoP positions coincide when the model is dynamically balanced (gravity and inertia forces are equal and opposite to contact forces).

In this study, we used OpenSim [7] modeling and simulation to examine ZMP-predicted ground reactions during single-leg landings and determine how sensitive predictions are to different kinematics. We hypothesized that: **H1**) the ZMP approach predicts ground reactions during single-leg landings and **H2**) predictions using dynamically-inconsistent kinematics produce larger root-mean-square errors (RMSE) from measured ground reactions compared with using more dynamically-consistent kinematics.

METHODS

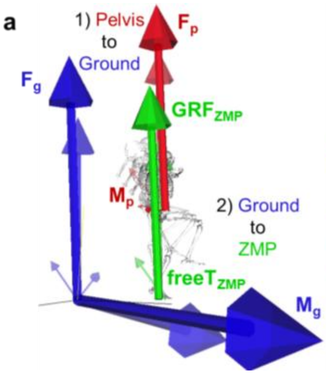
Eight male Western Australian Amateur Football players (20.5±1.77 yrs, 87.8±4.76 kg, 1.86±0.08 m) were randomly selected from a cohort participating in a single-leg jump landing protocol [3]. A 12-camera Vicon MX system recorded 3D marker trajectories at 250 Hz and an AMTI force platform recorded ground reactions at 2,000 Hz.

A 3D, full-body model with 37 actuated degrees of freedom was used in each simulation (Figure 1a) created with a 3-step process. First, the model was scaled to participant-specific anthropometry. Second, ***inverse kinematics*** (**IK**) determined model kinematics matching measured kinematic marker data. Third, a ***residual reduction algorithm*** (**RRA**) determined optimal actuator controls producing kinematics from a forward dynamic simulation, where optimization [4] minimized inconsistencies (residual forces and moments) between model dynamics and measured ground reactions.

The IK and RRA kinematics were separately used with the ZMP approach to predict ground reactions and compared with measured values. Inverse dynamics, without external contact loads applied, determined pelvis residuals. These residuals were transformed to an equivalent set of forces and moments about the inertial (ground) reference frame origin. Similar to the CoP, the ZMP approach further transformed these quantities to ZMP-predicted ground reactions, a set of forces and a single, free vertical torque (horizontal moments are 0), and located the ZMP in the ground reference frame.

RESULTS AND DISCUSSION

Confirming H1, ground reactions were accurately predicted during single-leg landings when the model used the RRA motion adjusted for dynamic inconsistencies (Figure 1b). The largest RMSE's were in the anterior reaction force (1.25 %BW) and lateral ZMP position (1.24 cm), likely due to minimized, but not eliminated, dynamic inconsistences. Confirming H2, predicted ground reactions were not accurate when the model used the dynamically-inconsistent IK motion. The largest RMSE's were in the vertical reaction force (73 %BW) and anterior ZMP position (154 cm), due to dynamically-inconsistent inverse kinematics, as the same skeletal model and any inherent modeling errors were used with both sets of kinematics for each participant.



b

ZMP Predictions	RMSE for 2 Kinematics	
	IK	RRA
GRF (%BW)	51.2	1.05
freeT (%BW*HT)	9.29	1.12
CoP (cm)	111	1.04

Figure 1: (a) Participant-specific model during landing and pelvis residuals (*red*) transformed to equivalent forces and moments about the ground origin (*blue*) to ground reactions from the Zero-Moment Point (ZMP) approach (*green*); (b) root-mean-square errors (RMSE) for all 8 participants.

CONCLUSIONS

The ZMP approach was able to predict ground reactions during single-leg landings; however, due to large accelerations and forces during this sport movement, dynamically-consistent kinematics are needed to make accurate predictions with the ZMP approach. Future work to determine whole-body kinematics minimizing lower-limb, knee, and ACL injury risk should constrain the ZMP position to remain under the landing foot.

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