JOINT REACTION FORCES BETWEEN HORIZONTAL AND VERTICAL JUMP TEST

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Abstract. *This study describes the joint reaction forces between horizontal and vertical jumps, considering the propulsion and landing phases. We analyzed nineteen healthy women that performed jumps in the horizontal and vertical directions. The joint reaction forces variables were calculated by the Opensim software tool. The static optimization was needed to estimate the muscle activation to use in joint reaction forces analysis. To use the estimate muscle activation, we compare these results with the collected muscle activation by electromyography. We observed that the hip's joint reaction forces were greater during the vertical propulsion and horizontal landing. Furthermore, the joint reaction forces were greater in the mediolateral axis in the ankle during vertical propulsion. These results help to evaluate compensatory movements when the subject has some injury or pain.*

Keywords*: Jump, Propulsion, Landing, Joint Reaction Forces, EMG.*

1. Introduction

Computational modeling has several features in different areas, including the health area, contributing with findings that directly influence clinical practice. It is possible to accurately measure deficits found in people who have some type of pain or injury with motion capture tools. Patients with knee osteoarthritis suffer from increased joint overload, generating pain. In a compensatory way, these patients change their way of moving, with greater ranges of movement of the hip and trunk, reducing the overload on the knee but increasing it on other joints. (MEIRELES, REEVES, *et al.*, 2019). Therefore, tools that can estimate forces on joints are important so that the health professional or coach can identify possible overloads and compensations and correct them. (LENHART, KAISER, et al., 2015).

In healthy subjects, we analyzed two types of single-leg jumps: maximum horizontal and vertical jumps, in their different phases: propulsion and landing. This study aims to analyze the forces of joint reactions of the lower limbs through computational calculations based on the biomechanical variables collected. This study will allow a better choice by the clinician about the most appropriate test depending on the presumed injury to be evaluated (ALVIM, DE SOUZA MUNIZ, *et al.*, 2019, HEEBNER, RAFFERTY, *et al.*, 2017). The OpenSim software was used to estimate the forces of joint reactions, using the muscle activation estimated by the static optimization tool of the software itself. The estimated muscle activation was compared with the muscle activation collected by surface electromyography (EMG) of certain muscles to validate the simulated results.

2. METHODS

2.1. Sample and experimental protocol

Nineteen healthy young women using the dominant limb were invited to participate in the study. All volunteers reviewed the study protocol and provided written consent. The study was approved by Clementino Fraga Filho University Hospital Ethics Committee of the Federal University of Rio de Janeiro, under CAAE number, 05764918.5.0000.5257.

We analyzed three maximum height (vertical) and maximum distance (horizontal) single-leg jumps, considering propulsion and landing phases. Joint reaction forces and muscles activations variables were compared among Horizontal Propulsion (HP), Vertical Propulsion (VP), Horizontal Landing (HL), and Vertical Landing (VL).

The volunteers were stimulated to jump with a single dominant leg ahead and horizontally as far as possible and vertically as high as possible. For both jumps, the upper limbs were at the side of the trunk and hands on the iliac crests. Each jump was repeated five times with one minute of rest between the tests, and the average of the three better jumps was calculated. The propulsion phase was determined by the interval started when the ground reaction force reached 90% of the volunteer's weight and ended when it was less than 10%. The landing phase was determined by the interval started when the first contact on the force platform (time of landing collision) occurred 5 seconds after the initial contact.

A BTS P-6000 force platform (BTS Bioengineering, Milan, Italy) with a sampling frequency of 400 Hz was used to capture ground reaction forces. Ground reaction force data were filtered by a Low Pass Butterworth zero-lag 4th order filter at 12 Hz using MATLAB®. Surface EMG data were recorded using a wireless probe (FREE EMG, BTS Bioengineering, Milan, Italy) with nine channels, sampling at 1,000 Hz per channel digitalized by a 16-bit A/D converter synchronized with kinematic and force plate data. After skin preparation, Ag/AgCl surface electrodes (Medi-Trace 200

Kendall Healthcare/Tyco, Canada), spaced 2cm from center to center, were positioned according to HERMENS, FRERIKS, *et al.*, (2000). The chosen muscles were gluteus maximus, gluteus medius, biceps femoris (long head), rectus femoris, vastus lateralis and medialis, tibialis anterior, gastrocnemius lateralis and medialis of the evaluated leg.

Electrode cables were connected to a portable wireless amplifier with a common-mode rejection ratio higher than 100 dB, output impedance exceeding 10 MΩ, cutoff frequency of 20-500 Hz, and a gain of 1,000x. EMG data were rectified offline and filtered with a 10 Hz low-pass, zero-lag, second-order Butterworth filter. All signals were normalized by the peak of EMGs.

2.2. Biomechanical models and data processing

In OpenSim software, we use twenty-one rigid-bodies, 92 muscles, and 37 generalized coordinates (GC) model of the whole human body was modified to allow right and left knee adduction/abduction, adding two more GCs (ALVIM, DE SOUZA MUNIZ, *et al.*, 2019, HAMNER, SETH, *et al.*, 2010). The upper limbs were locked for moving with the trunk during the test. Trunk, pelvis, thigh, and shank length and center of mass position were scaled for each subject. The mass was scaled, preserving mass distribution among body segments.

We used OpenSim's static optimization tool to estimate the activations and muscle forces of the model. In this tool, the net torques of each joint are used, which are divided into individual muscle forces. Muscle forces are determined by minimizing the sum of squares of muscle activations raised to a given power. In addition, the static optimization calculates the strength of the active muscle fiber considering the pennation angle as being fixed. (THELEN, 2003).

We used the Geers error calculation method to calculate the errors between muscle activations collected by the EMG and estimated by the static optimization. Through this method, magnitude (M), phase (P) and global error (C) errors are calculated, which combine magnitude and phase errors and generate a single global error value. (ALVIM, LUCARELI, *et al.*, 2018, GEERS, 1984).

The tool Joint Reaction Forces (JRF) of OpenSim is used to calculate the resultant forces and moments at joints. That calculating considers the joint forces and moments transferred between consecutive bodies as a result of all loads acting on the model. That load represents all un-modeled structures at the joint such as cartilage contact and ligaments, to produce the desired movements. The JRL uses the estimated muscles forces of the static optimization to achieve the results.

We calculated the maximum value and the standard deviation of each variable of joint reaction forces. Then, we compared the differences of these variables between HP and VP and between HL and VL. We applied Anova two-way for parametric variables and the Friedman test for non-parametric data from the joint reaction analysis. The Tukey post hoc test was used for parametric data and the Wilcoxon post hoc test for non-parametric variables, with a significance of 95%, $\rho < 0{,}05$.

3. Results and Discussion

We arrived at estimated muscle activation values close to those collected by EMG (Figure 1**Erro! Fonte de referência não encontrada.**). Through the error calculations between the collected and estimated muscle activation, we obtained errors close to zero, which validate the comparison between the activation data (Table 1) (GEERS, 1984).

Table 2 shows the maximum and percentiles of joint reaction forces in three planes x (mediolateral), y (vertical) and z (anteroposterior). Some variables presented significant differences between the interaction of the type and phases of the jumps. According to the post-hoc interaction analysis between variables, we observed that the JRF of the hip joint on the vertical axis was higher in HA about HP and VA. However, it was lower than VP. The greater JRF in VP may be related to the vertical position of the trunk, which generates less flexion of the hip and knee, resulting in greater activation of the quadriceps femoris muscles, increasing joint overloads. (BLACKBURN, PADUA, 2009). In the anteroposterior axis of the hip, we observed that the joint reaction force was in the posterior direction and greater in the propulsion phase, HP and VP, in relation to VA. In the ankle joint, we found a greater JRF in the mediolateral direction of VP in relation to HP, VA and HA. Movements in the frontal plane mediolateral axis are important predictors of tibial movement and whether there is increased overload on the ligaments. In the case of reduced movements in this plane, there is a greater tendency for the strain on the knee ligaments. (VAN ROSSOM, WESSELING, *et al.*, 2019). In the anteroposterior ankle axis, the JRF of HA was greater than VA, in the posterior direction, possibly because in the horizontal landing, there is a greater acceleration of the tibia in relation to the vertical landing, so the collision of the foot on the ground can generate an increase in the JRF in this plane (VAN DER WORP, DE POEL, *et al.*, 2014). We have not found effects of interactions on the knee joint.

In conclusion, we observed greater joint overloads on the vertical axis at the hip joint in vertical propulsion and horizontal landing. In addition, we found forces on the hip joint on the posterior axis greater in horizontal and vertical propulsion. We found even higher values of joint overload in the medial-lateral direction in the ankle during vertical propulsion. These findings are important as predictors of pain or injuries when compared to patients with a certain orthopedic comorbidity, generating compensation, or improving the performance of a certain sports movement in athletes.

Table 1: Values referring to magnitude (M), phase (P) and global error (C) errors of the phases: horizontal propulsion (HP), horizontal landing (HA), vertical propulsion (VP) and vertical landing (VA).

HP	Gluteus Maximus	Gluteus Medius	Rectus Femoris	Vastus Lateralis	Vastus Medialis	Biceps Femoris	Tibialis Anterior	Gastrocnemius Lateralis	Gastrocnemius Medialis
M	0.55	1.54	-0.13	0.66	-0.21	0.29	-0.12	0.27	-0.65
P	0.14	0.21	0.17	0.13	0.11	0.24	0.17	0.17	0.27
C	0.57	1.56	0.21	0.67	0.23	0.37	0.21	0.32	0.71
HA									
M	1.00	0.46	-0.47	0.38	-0.59	-0.15	-0.38	0.28	-0.68
P	0.08	0.18	0.35	0.18	0.06	0.18	0.13	0.27	0.29
C	1.00	0.49	0.58	0.42	0.59	0.24	0.40	0.38	0.74
VP									
M	0.96	0.36	-0.63	0.41	-0.12	0.63	-0.05	0.33	-0.64
P	0.18	0.17	0.25	0.18	0.13	0.23	0.10	0.17	0.28
C	0.98	0.39	0.67	0.45	0.18	0.67	0.11	0.37	0.69
VA									
M	0.11	0.37	-0.51	-0.10	-0.65	-0.20	-0.17	0.05	-0.54
P	0.15	0.30	0.27	0.14	0.08	0.19	0.09	0.17	0.36
C	0.19	0.48	0.58	0.17	0.66	0.27	0.19	0.17	0.65

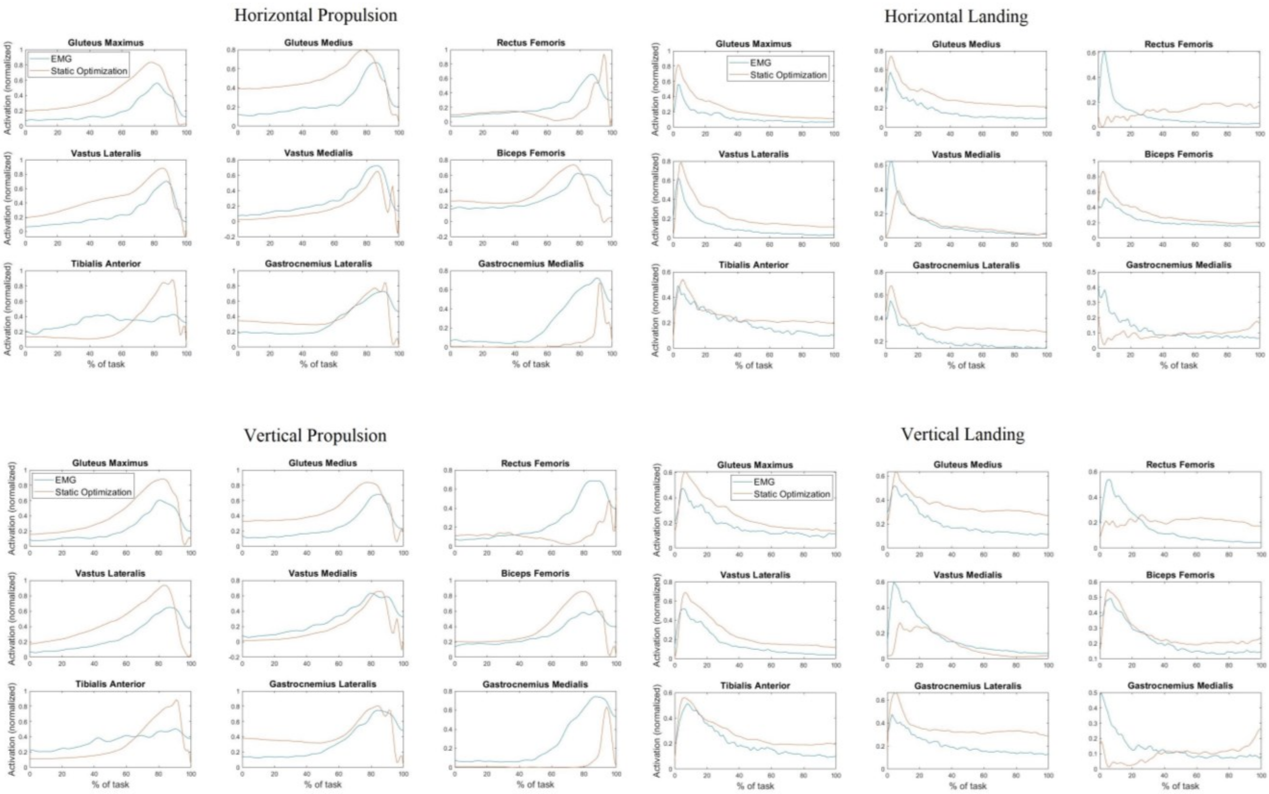

Figure 1: The graphs show the comparison between the muscle activations collected by the EMG (blue line) in relation to the muscle activation estimated by the Opensim static optimization tool (red line), during the horizontal and vertical propulsion and landing phases.

Table 2: Mean, standard deviation, maximum and percentiles of kinematics and dynamics data. Paired Wilcoxon test was used for differences with ρ = 0,05. Flex: Flexion; Ext: Extension; Std: standard deviation. HP: horizontal propulsion; VP: vertical propulsion; HL: horizontal landing; VL: vertical landing. The asterisks represent significant differences in the joints (deg: degrees) and moments with (Nm: Newton-meters).

	Propulsion phase				Landing phase					
Joint Reaction Force (N/BW)	Horizontal		Vertical		Horizontal		Vertical		p value	η^2
	Mean (SD)	CI95% (LB,UB)	Mean (SD)	CI95% (LB,UB)	Mean (SD)	CI95% (LB,UB)	Mean (SD)	CI95% (LB,UB)		
HipFx	1.13 (0.23)	1.02; 1.24	1.13 (0.30)	0.99; 1.28	0.67 (0.36)	0.50; 0.85	0.61 (0.29)	0.47; 0.75	0.6360	-0.79
HipFy*	2.97 (0.36)	2.80; 3.14	3.24 (0.52)	2.99; 3.49	3.07 (0.83)	2.67; 3.47	2.60 (0.62)	2.30; 2.90	0.0094	0.13
HipFz NP	-0.79	-1.07; -0.55	-0.93	-1.19; -0.61	-0.65	-0.96; -0.26	-0.45	-0.84; -0.27	0.0933	0.42
KneeFx* NP	-2.45	-2.86; -2.01	-2.43	-2.95; -2.08	-1.10	-0.96; -0.26	-1.01	-1.93; -0.57	0.0000	0.78
KneeFy	2.76 (0.27)	2.63; 2.89	2.74 (0.40)	2.55; 2.93	2.60 (0.54)	2.34; 2.86	2.47 (0.49)	2.24; 2.71	0.5721	-0.25
KneeFz*	-0.05 (0.27)	-0.18; 0.09	-0.041 (0.25)	-0.16; 0.08	-0.09 (0.23)	-0.20; 0.03	-0.04 (0.24)	-0.16; 0.08	0.0000	-0.19
AnkleFx NP	1.16	1.01; 1.46	1.20	0.88; 1.41	0.56	0.27; 0.78	0.48	0.37; 0.84	0.7280	-0.76
AnkleFy*	3.08 (0.62)	2.78; 3.38	3.13 (0.63)	2.83; 3.43	2.57 (0.81)	2.18; 2.96	2.49 (0.68)	2.16; 2.82	0.0240	-0.56
AnkleFz NP	-0.01	-0.07; 0.01	-0.01	-0.06; 0.01	-0.09	-0.11; -0.02	-0.07	-0.11; 0.01	0.6787	-0.37

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5. CONFLICT OF INTEREST STATEMENT

The present work did not present conflicts of interest.