Journal of Biomechanics 47 (2014) 1904–1908

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Short communication

A motion analysis marker-based method of determining centre of pressure during two-legged hopping

Laura-Anne M. Furlong*, Andrew J. Harrison

Biomechanics Research Unit, Department of Physical Education and Sport Sciences, University of Limerick, Castletroy, Limerick, Ireland

ARTICLE INFO

Article history:
Accepted 7 April 2014

Keywords:
Kinematics
Inverse dynamics
Regression
Force plate
Hopping frequency

ABSTRACT

The fixed position of force plates has led researchers to pursue alternative methods of determining centre of pressure (CoP) location. To date, errors reported using alternative methods to the force plate during dynamic tasks have been high. The aim of this study was to investigate the accuracy of a motion analysis marker-based system to determine CoP during a two-legged hopping task. Five markers were attached to the left and right feet of eight healthy adults (5 females, 3 males, age: 25.0 ± 2.8 years, height: 1.75 ± 0.07 m, mass: 71.3 ± 11.3 kg). Multivariate forward stepwise and forced entry linear regression was used with data from five participants to determine CoP position during quiet standing and hopping at various frequencies. Maximum standard error of the estimate of CoP position was 12 mm in the anteroposterior direction and 8 mm in the mediolateral. Cross-validation was performed using the remaining 3 participants. Maximum root mean square difference between the force plate and marker method was 14 mm for mediolateral CoP and 20 mm for anteroposterior CoP during 1.5 Hz hopping. Differences reduced to a maximum of 7 mm (mediolateral) and 14 mm (anteroposterior) for the other frequencies. The smallest difference in calculated sagittal plane ankle moment and timing of maximum moment was during 3.0 Hz hopping, and largest at 1.5 Hz. Results indicate the marker-based method of determining CoP may be a suitable alternative to a force plate to determine CoP position during a two-legged hopping task at frequencies greater than 1.5 Hz.

1. Introduction

Centre of pressure (CoP) refers to the point of application of the ground reaction force which is normally acquired using a force plate (FP). CoP position, position change and magnitude of area within which it moves are of interest to researchers during both standing and dynamic tasks such as hopping, walking and running (Han et al., 1999; Hertel et al., 2006; Lafond et al., 2004). It is also used as an input for inverse dynamics calculations of joint torques (McCaw and Devita, 1995). The fixed location of most FPs has led researchers to attempt to find more mobile alternatives to determine CoP position such as in-shoe devices (Chesnin et al., 2000; Forner Cordero et al., 2004; Fradet et al., 2009). However, due to large reported differences between the FP and these methods, the FP still remains the most commonly used method of obtaining CoP.

Root mean square difference (RMSD) between CoP determined using a FP and in-shoe measurement systems has previously been reported to be between 15 mm during quiet standing and 41 mm during walking (Chesnin et al., 2000; Fradet et al., 2009). Differences are most likely due to insole movement, incorrect transformation of co-ordinates from local to global systems or temporal synchronisation error (O'Connor et al., 1995). Pillet et al. (2010) used a motion analysis anthropometric-based model to determine CoP in static and self-selected speed walking tasks. RMSD was between 14.2 ± 5.2 and 17.6 ± 5.7 mm in the mediolateral (ML) direction and 33.0 ± 4.2 mm and 43.4 ± 5.7 mm in the anteroposterior (AP) direction. Shifts in CoP of these magnitudes have been shown to significantly affect sagittal plane joint torque calculation by 19.5–48.2% (Kim et al., 2007; McCaw and Devita, 1995).

Motion analysis is often used to determine kinematics during dynamic tasks. Use of a motion analysis marker-based method of determining CoP could allow researchers and clinicians to measure CoP in a variety of locations. The aim of this study was to investigate the accuracy of a motion analysis marker-based method to determine CoP by comparing values obtained with those obtained from a FP. Ideally this would use as few markers as possible and return similar values to the FP.

2. Methods

2.1. Participants and participant preparation

Following university ethics committee approval, 8 healthy, active adults (5 females; 3 males; age, 25.0 ± 2.83 years; height, 1.75 ± 0.07 m; mass, 71.3 ± 11.3 kg) consented to

* Corresponding author. Tel.: +353 61 234715.
E-mail address: laura-anne.furlong@ul.ie (L.-A. Furlong).

http://dx.doi.org/10.1016/j.jbiomech.2014.04.008
0021-9290/

participate in this study. Retro-reflective markers (9.5 mm) were attached to the superior first and third metatarsophalangeal joints (1MTP and 3MTP), lateral fifth metatarsophalangeal joint (5MTP), at half the length of the foot in line with 3MTP (mid-foot; MF) and on the superior foot at the point where it joined the leg (groove; GR). Familiarisation consisted of at least 10 hops at each test frequency (1.5 Hz, 2.2 Hz, 3.0 Hz and a self-selected frequency) until participants were striking the FP in time with the digital metronome (TempoPerfect Metronome Software v2.02, NCH Software, Canberra, Australia).

2.2. Data acquisition

All trials were captured using a 6 camera 3D motion analysis system (300 Hz, MAC Eagle, Motion Analysis Corporation Inc., Santa Rosa, CA., USA) and 2 AMTI force plates (300 Hz, AMTI OR6-7, Watertown, MA., USA). This sample rate was considered appropriate as the purpose of data collection was to obtain simultaneous marker kinematics and CoP data rather than investigate changes in CoP position or force with time. Testing consisted of 2 two-legged hopping trials of 30 s duration at each test frequency with one foot on each FP and during quiet standing. The two-legged hopping movement was similar to that performed by Farley and Morgenroth (1999) and Hobara et al. (2010), where the 2 feet were positioned hip width apart and both legs jumped simultaneously in place. FP *X* and *Y*-axes were aligned to the ML and AP directions respectively. The FP was re-zeroed between every trial to minimise drift, however some trials required re-zeroing in post-processing to produce a zero force value when nothing was on the plate.

2.3. Data processing

Markers were filtered using a fourth order, zero lag, low-pass Butterworth filter in the motion analysis software with cut-offs of 14 Hz (1MTP, 3MTP), 13 Hz (5MTP) and 17 Hz (MF, GR) based on residual analyses (Winter, 2005). CoP data calculated using vertical forces of less than 100 N and occurring in the outer 10 cm edges of the FP were removed from analysis due to previously reported inaccuracies in CoP measurement at low force levels and the outer edges of the FP (Bobbert and Schamhardt, 1990; Middleton et al., 1999). Only ML CoP data occurring within the width of the foot were included in analysis due to the improbability of the CoP being outside the foot when the foot was in contact with the plate at high forces.

2.4. Error checking

A calibrated mass (9.815 kg) was placed on the FP close to the centre of the plate, then to the right, left, behind and front of this position for 30 s each to estimate CoP deviation when an inanimate object was placed on it. The influence of zeroing in post-processing was estimated by comparing the same trial twice with the trial zeroed at different points.

2.5. Statistical analysis

All statistical analysis was completed using SPSS Statistics 20 (IBM, Armonk, NY, USA). CoP data from five participants were used for initial equation derivation. Multivariate forward stepwise linear regression ($p_{\text{in}}=0.05$, $p_{\text{out}}=0.10$) was used to derive frequency-specific equations for predicting CoP position from marker position data in the *X*-, *Y*- and *Z*-axes. The most important markers to predict CoP in ML and AP directions were identified with consideration to prevalence in equations and practicalities of marker location. Co-ordinate data from all three axes for these markers were then entered into multivariate forced entry linear regression (Table 4). To clarify presentation, standard error of the estimate and cross-validation results are presented in millimetres.

2.6. Cross-validation and establishment of difference between methods

Adjusted R^2 was calculated during forced entry regression to provide an estimate of explained variance in the population. Cross-validation was completed using data from the remaining three participants to determine how well the model predicted CoP in similar adults from outside the sample. RMSD between CoP measured using the FP and the marker-based method was calculated for these participants. 95% confidence interval (CI) of the difference between the two methods for all eight participants was calculated to provide an estimate of the predictive ability of the equations. Pearson's *r* was calculated to investigate the strength of the linear relationship between the two methods with the correlation considered very large when between 0.7 and 0.9, and 'nearly perfect' when greater than 0.9 (Hopkins, 2006).

Table 1
Number of data points used in multivariate forward stepwise and forced entry regression.

Frequency (Hz)	Number of data points used		
	Mediolateral left	Mediolateral right	Anteroposterior
Quiet standing	5355	13277	18632
1.5	4804	10452	15256
2.2	5337	4682	10019
3.0	4698	9495	14193
Self-selected	6382	6586	12968

Table 2
Number of data points used in cross-validation of regression equations.

Frequency (Hz)	Number of data points used		
	Mediolateral left	Mediolateral right	Anteroposterior
Quiet standing	4691	2144	6835
1.5	1654	3340	4994
2.2	1014	2298	3312
3.0	3235	3787	7022
Self-selected	11778	3598	15376

Table 3
Initial multivariate forward stepwise regression analysis to identify main predictors of centre of pressure position in mediolateral and anteroposterior directions.

Frequency and direction	Predictors used	R^2	SEE (mm)
Quiet standing (left)	MF_X, GR_Y	0.999	1
	$5MTP_X$, $MF_{X,Z}$, GR_X	0.999	1
	Full model	0.999	1
Quiet standing (right)	$MF_{X,Z,}$ GR_Z	0.997	1
	$3MTP_Z$, $MF_{X,Z,}$ GR_Z	0.997	1
	Full model	0.998	1
Quiet standing (anteroposterior)	$3MTP_Z$, $5MTP_Y$	0.937	7
	$3MTP_Z$, $5MTP_{Y,Z,}$ $MF_{Y,Z}$	0.959	6
	Full model	0.989	3
1.5 Hz mediolateral (left)	$1MTP_X$ and GR_X	0.987	5
	$1MTP_{X,Z,}$ $5MTP_Z$ and GR_X	0.993	3
	Full model	0.994	3
1.5 Hz mediolateral (right)	$1MTP_X$ and $5MTP_X$	0.960	6
	$1MTP_X$, $5MTP_X$ and MF_Z	0.965	6
	Full model	0.985	4
1.5 Hz (anteroposterior)	$MF_{Y,Z}$, $1MTP_Y$	0.959	14
	$MF_{Y,Z,}$ $1MTP_{Y,Z,}$ $3MTP_X$	0.964	13
	Full model	0.972	11
2.2 Hz mediolateral (left)	$1MTP_Z$ and $3MTP_X$	0.914	9
	$1MTP_Z$, $3MTP_{X,Z,}$ $5MTP_Z$	0.920	8
	Full model	0.928	8
2.2 Hz mediolateral (right)	$1MTP_{X,Y,Z,}$ $MF_{X,Z}$	0.964	4
	$1MTP_{X,Y,Z,}$ $MF_{X,Z,}$ GR_X	0.965	4
	Full model	0.968	4
2.2 Hz (anteroposterior)	$MF_{Y,}$ $1MTP_Y$	0.960	11
	$MF_{Y,}$ $1MTP_Y$, $5MTP_Z$	0.964	10
	Full model	0.973	9
3.0 Hz mediolateral (left)	$1MTP_Z$ and $3MTP_X$	0.976	4
	$1MTP_{Z,}$ $3MTP_{X,}$ $5MTP_Z$	0.985	3
	Full model	0.987	3
3.0 Hz mediolateral (right)	$1MTP_{X,}$ GR_X	0.988	5
	$1MTP_X$, $3MTP_{X,}$ GR_X	0.991	4
	Full model	0.996	3
3.0 Hz (anteroposterior)	MF_Y and $3MTP_Y$	0.977	9
	$MF_{Y,}$ $3MTP_{Y,}$ $5MTP_Y$	0.978	9
	Full model	0.986	7
Self-selected mediolateral (left)	$3MTP_X$, GR_X	0.977	8
	$3MTP_X$, $GR_{X,Z,}$ $5MTP_Z$	0.980	7
	Full model	0.983	7
Self-selected mediolateral (right)	$1MTP_X$, $5MTP_{X,Z}$	0.971	5
	$1MTP_{X,}$ $5MTP_{X,Y,Z,}$ $3MTP_X$	0.977	4
	Full model	0.985	3
Self-selected (anteroposterior)	$MF_{Y,Z,}$ GR_Y	0.963	11
	$1MTP_Z$, $MF_{Y,Z,}$ GR_Y	0.965	11
	Full model	0.972	10