ISB 2013 BRAZIL
XXIV CONGRESS OF THE INTERNATIONAL SOCIETY OF BIOMECHANICS
XV BRAZILIAN CONGRESS OF BIOMECHANICS

THE EFFECT OF COP ERRORS ON JOINT MOMENTS AT DIFFERENT GAIT VELOCITIES

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SUMMARY

The aim of this study was to investigate the effect of errors in the location of the center of pressure (5 and 10 mm) on joint moment uncertainties at different gait velocities (1.0, 1.5, and 2.0 m/s). Joint moments of five healthy young adults were calculated by inverse dynamics using the bottom-up approach. Results indicated that there is a linear relationship between errors in center of pressure and absolute joint moment uncertainties. The absolute moment peak uncertainties expressed on the anatomic reference frames decreased from distal to proximal joints, except for the abduction moments. There was an increase in moment uncertainty (up to 0.04 Nm/kg for the 10 mm error in the center of pressure) from the lower to higher gait velocity, although not for hip or knee abduction. Finally, depending on the plane of movement and the joint, relative uncertainties experienced variation between 5 and 31%, and the knee joint moments were the most affected.

INTRODUCTION

In the bottom-up method of inverse dynamics (ID), errors in the estimates of variables generate uncertainties in joint moments (ΔM) that propagate throughout the kinematic chain. Anthropometric parameters [1-3], segment angles [3], external force [4], and center of pressure location (CoP) [3-5] are among the main factors associated with ΔM. Although they can be somewhat clarifying, the findings about ΔM that are based on 2D analysis of locomotion cannot be generalized for all ID 3D analyses [6, 7]. Furthermore, because ground reaction force is affected by locomotion velocity and CoP defines the application point of this external force on the kinematic chain's most distal segment, one could expect that the significance of CoP error depends on velocity. The aim of this study was to investigate the effect of manipulating the CoP on uncertainties in lower limb joint moments (M) calculated by 3D bottom-up ID at slow, natural, and fast gait velocities. The hypotheses were that errors in the CoP location propagate to M, causing ΔM to decrease from distal to proximal joints, and from higher to lower gait velocities, and, because of the combination of these factors (kinematic chain configuration and velocity), the highest potential uncertainty would befall the ankle moments during fast gait.

METHODS

Five healthy male subjects (23.2±2.7yr; 74.6±8.0kg, and 1.78±0.01m) participated in this experiment, which was approved by the local research Ethics Committee. The subjects were instructed to walk at different velocities (slow = 1.0; natural = 1.5, and fast = 2.0 m/s, 5% variation tolerance). The kinematic and ground reaction force data were filtered using a Butterworth filter, with cut-off frequencies defined by residual analysis.

The human body was modeled by four linked segments (foot, shank, thigh, and pelvis) and the anthropometric parameters were adopted from Zatsiorsky [8], using the adjustments proposed by De Leva [9]. This model was adopted in order to minimize the effects of the segment inertia parameters on the ΔM [2]. The calibrated anatomical system technique [10] was used in the interest of minimizing errors in kinematic data measurement [11]. Particularly in the case of the hip, the hybrid prediction method, proposed by Bell et al. [12], was adopted, so that the potential error in locating the joint center would be reduced [13]. The data were expressed in global (GRS) and local anatomic (LRS-a) reference systems. The coordinates of the CoP were calculated at all gait velocities, and 5 and 10 mm shifts were applied to it in both directions simultaneously. The net joint moments were obtained by successively applying the Newton and Euler equations to the foot, shank, and thigh segments. The ΔM propagation was calculated according to Kline and McClintock´s equation [14]. The maximum peaks, or minimum, depending on the joint action, of the resulting M and the associated ΔM were compared across different gait velocities by means of repeated measure ANOVAs, followed by post hoc Newman-Keuls tests (α=5%). In addition, the relative uncertainties ($\Delta M/M$) were defined for the peaks M at each joint and velocity.

RESULTS AND DISCUSSION

The overall results showed that CoP shifting caused a decrease in ΔM (particularly for medial/lateral rotation or inversion/eversion and flexion/extension) from distal to proximal joints, and an increase in ΔM with an increase of gait velocity. However, relative ΔMs were not the highest in the most distal joint on fast gait (Table 1). The linear dependency between CoP shifting (5 and 10 mm) and ΔM, already observed in the literature [3, 5], was confirmed to be independent of movement plane and gait velocity in this study. The explanation for that result lies in the linear dependency between ΔM and moment arm errors, and the propagation of the ΔM from distal to proximal segments. Because of the significant changes in the M components, the choice of different reference systems [7, 15] (global or local) may alter $\Delta M/M$, especially for M components about the longitudinal axes of the segments.

By observing the ΔM/M, it was possible to identify that knee M peaks were the most affected by CoP shifting, as it was observed in 2D analysis [5]. This was because, for this joint, the instants of M and ΔM peak occurrence are rather coincident (between 20–30% of the stance phase) and the absolute difference of their magnitudes are smaller. Consequently, the ΔM/M were more critical at peaks medial/lateral (or inversion/eversion) and adductor/abductor M, and at slow gait, for which M magnitudes are smaller. Given the linearity between ΔCoP and ΔM, the uncertainties can be reported as uncertainties per unit of error in the CoP location. At the instants of peak M, maximum uncertainty values of 0.012 Nm/kg/mm (slow gait), 0.014 Nm/kg/mm (natural gait), and 0.015 Nm/kg/mm (fast gait) were found, consistently increasing from proximal to distal. Errors in the CoP location in the range of 5–10 mm are likely in typical gait analysis applications [5]. In particular, due to limitations in the equipment, CoP errors can be more than 3 mm for strain gauge force plates embedded in the ground [16], or up to 20 mm for those mounted on treadmills [17] and for piezoelectric force plates [18]. Consequently, for instance, extension ΔM in the knee of up to 0.20 Nm/kg can occur, corresponding to 28% of the peak extension M in this joint observed at the natural gait velocity, and 62 and 22% at the slow and fast gait velocities, respectively.

Improvements in the body motion reconstruction based on optimization techniques [19], alternative ID schemes [4, 20] and the use of correction algorithms [18] may improve estimations of the CoP location with respect to the lower limb or mitigate the problem. We emphasize that our results are relevant in clinical assessments, as the expected magnitude of the ΔM resulting from errors in the CoP location has been established for different walking velocities.

CONCLUSIONS

The uncertainties in joint moment peaks, calculated by 3D bottom-up inverse dynamics, decreases from distal to proximal segments at the transverse and sagittal planes in any gait velocity when expressed in LRS-a. Those uncertainties were directly proportional to gait velocity, except for the knee and hip abductor peaks. Knee joint moments were the most affected by the shift in center of pressure, because of higher similarity between the patterns of the moment and uncertainty magnitudes. The uncertainties were especially critical for medial/lateral (or inversion/eversion) and abductor/adductor moments at slow gait.

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Table 1: Means and standard deviations of moment peaks (M) without perturbation and uncertainties (ΔM) caused by CoP shifting (delta = 10 mm), and relative uncertainty (ΔM/M) at different gait velocities (V) [slow (s), natural (n) and fast (f)].

Variable	V	Ankle			Knee			Hip		
		inversion	abduction	extension	medial rot.	abduction	extension	lateral rot.	abduction	extension
ΔM/M	s	0.20	0.22	0.09	0.29	0.30	0.31	0.09	0.12	0.06
	n	0.26	0.11	0.09	0.25	0.27	0.14	0.10	0.13	0.05
	f	0.27	0.11	0.08	0.27	0.29	0.11	0.14	0.12	0.07

Note: The lowest relative ΔM occurred in the hip, particularly in extensor peak (5 to 7%) at all velocities, and the highest uncertainties were found in all knee moments, especially during slow gait (29 to 31%).