Lower limb inertial parameter changes during the swing and ground contact phases at different running velocities

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SUMMARY

Soft tissue motion can contribute to inertial parameters changing during locomotion. Moment of inertia (MOI) changes due to soft tissue motion were calculated using marker arrays on the lower limb during different running velocities in a group of runners. The average MOI changes associated with damped soft tissue motion during running were 13.2 ± 2.9 %, 14.5 ± 3.0 %, 16.3 ± 5.8 % with respect to X, Y, Z axes on the thigh, 11.2 ± 2.1%, 9.4 ± 2.1, 20.2 ± 5.3 % respectively on the shank.

INTRODUCTION

Whole-body level biomechanical analyses often assume that human limbs behave as rigid bodies with constant inertial parameters. However, the human body is mainly composed of deformable soft tissue. Soft tissue center of mass (COM) motion relative to the rigid body frame can reach 1.4 cm, and variations in the moment of inertia (MOI) can reach 17 % during drop landing tasks [1]. As similar intensity impacts occur during running, similar changes in inertial characteristics would be expected but this is currently unknown. The aim of this study was to investigate changes in the inertial parameters of the lower limb during running at different speeds.

METHODS

Ten healthy, university-level male runners (age: 24 ± 4.2 years, height: 1.77 ± 0.08 m, mass: 79.56± 10.5 kg) gave informed consent and had the soft tissue motion of the shank and thigh quantified in 3D via 8x9 arrays of 6.4 mm reflective markers (details in [1]). Marker positions were determined using a 17-camera motion analysis system sampling at 750 Hz (Vicon Vantage, Oxford Metrics PLC., Oxford, UK) as subjects ran barefoot on an instrumented treadmill (3DI, Treadmetrix, Park City, UT, USA) at three testing velocities (2.5, 3.5 and 4.5 m/s).

Data were reconstructed, labelled and gap filled using Nexus 2.7 (Oxford Metrics PLC, Oxford, UK). Further post-processing was completed using custom-written MATLAB code (R2023b, MathWorks, Natick, MA., USA), including low-pass filtering at 100 Hz with a 4th order, zero lag Butterworth filter. Frame by frame segment volumes from marker arrays were represented as a collection of tetrahedra using the Delaunay triangulation method and the full inertial parameters of the soft tissue within the array were calculated using the methods in [1]. Distances between the fixed segment COM, from inverse kinematics based on joint markers, and the soft tissue COM were determined. The MOI of the soft tissue volume about the rigid COM were calculated using the parallel axis theorem about the sagittal axis (X), transverse axis (Y) and longitudinal axis (Z).

RESULTS AND DISCUSSION

The average mass of thigh and shank, as calculated from the marker arrays were 6.2 ± 1.15 kg and 2.9 ± 0.61 kg, respectively. The percent changes in MOI values (Table 1) are comparable to those reported in jumping tasks [3]. Group mean results indicated greater MOI changes at higher running speeds (Table 1), except for the shank during swing. Significant speed effects were observed around the sagittal axis on the thigh during both phases and around the transverse axis during swing ($p \leq 0.037$). Similarly, significant effects were seen around the sagittal and transverse axes of the shank during ground contact (GC) ($p \leq 0.032$). These results agree with previous suggestions that the soft tissue work increased with greater impacts, which occur at higher running speed [2]. Surprisingly at first, there was greater MOI change in swing phase compared to GC phase, for both segments. This can be explained by the lower muscle stiffness during swing and the greater range of active motion during the swing [2,3] resulting in larger, but compared to GC, slower changes.

Table 1. Percentage changes relative to static values in MOI about X, Y, Z axes during barefoot running at 2.5, 3.5 and 4.5 m/s.

	Phase	Speed (m/s)	Ix (%)	Iy (%)	Iz (%)
Thigh	Swing	2.5	9.2 ± 2.1	9.4 ± 2.8	12.8 ± 4.3
		3.5	11.3 ± 2.4	11.9 ± 3.5	14.7 ± 6.1
		4.5	12.4 ± 2.6	13.9 ± 4.5	15.6 ± 5.8
	GC	2.5	6.9 ± 1.8	8.7 ± 2.2	9.1 ± 2.6
		3.5	7.6 ± 3.0	8.3 ± 3.1	9.7 ± 3.1
		4.5	8.5 ± 2.8	8.8 ± 3.0	10.3 ± 2.9
Shank	Swing	2.5	10.6 ± 2.8	8.3 ± 2.1	18.6 ± 5.7
		3.5	10.2 ± 2.9	8.6 ± 1.9	18.7 ± 5.8
		4.5	8.9 ± 2.8	8.5 ± 2.1	18.4 ± 6.5
	GC	2.5	8.5 ± 1.2	5.3 ± 1.5	13.4 ± 2.9
		3.5	9.1 ± 1.7	5.9 ± 1.7	14.6 ± 4.0
		4.5	9.5 ± 1.4	6.6 ± 2.1	14.8 ± 3.4

CONCLUSIONS

Marker arrays are capable of determining substantial changes in inertial parameters during different running conditions. Results indicate that MOI changed greater at higher velocities and within the swing phase.

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