Journal of Electromyography and Kinesiology 31 (2016) 55–62

Contents lists available at ScienceDirect

Journal of Electromyography and Kinesiology

journal homepage: www.elsevier.com/locate/jelekin

Lower limb joint stiffness and muscle co-contraction adaptations to instability footwear during locomotion

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ARTICLE INFO

Article history:
Received 2 July 2016
Received in revised form 12 September 2016
Accepted 18 September 2016

Keywords:
Unstable footwear
Perturbations
Joint stability
Walking
Running

ABSTRACT

Unstable shoes (US) continually perturb gait which can train the lower limb musculature, but muscle co-contraction and potential joint stiffness strategies are not well understood. A shoe with a randomly perturbing midsole (IM) may enhance these adaptations. This study compares ankle and knee joint stiffness, and ankle muscle co-contraction during walking and running in US, IM and a control shoe in 18 healthy females. Ground reaction forces, three-dimensional kinematics and electromyography of the gastrocnemius medialis and tibialis anterior were recorded. Stiffness was calculated during loading and propulsion, derived from the sagittal joint angle-moment curves. Ankle co-contraction was analysed during pre-activation and stiffness phases. Ankle stiffness reduced and knee stiffness increased during loading in IM and US whilst walking (ankle, knee: $p = 0.008$, 0.005) and running ($p < 0.001$; $p = 0.002$). During propulsion, the opposite joint stiffness re-organisation was found in IM whilst walking (both joints $p < 0.001$). Ankle co-contraction increased in IM during pre-activation (walking: $p = 0.001$; running: $p < 0.001$), and loading whilst walking ($p = 0.003$), not relating to ankle stiffness. Results identified relative levels of joint stiffness change in unstable shoes, providing new evidence of how stability is maintained at the joint level.

1. Introduction

Unstable shoes (US) can be used as functional training devices, as increased muscle activation is required to make postural adjustments and keep the body balanced. This often presents as increased levels of co-contraction when an individual is initially exposed to US (Horsak et al., 2015; Buchecker et al., 2012). Co-contraction can distribute internal forces more evenly (Baratta et al., 1988), and may be important for injury prevention (Hirokawa et al., 1991). Mechanical joint stiffness is derived by muscle stiffness, which the neuro-muscular system controls by adjusting muscle activation level (Hogan, 1984; Lee et al., 2006). If this relates to the increased co-contraction at the joint to help stabilise locomotion remains unknown. A stiffer joint will resist displacement from an external perturbation, possibly preventing excessive joint motion and injury (Riemann et al., 2002). On the other hand, moderately reduced range of motion has also been linked with reduced limb stability (Kim and Lockhart, 2012; Salsich and Mueller, 2000).

Previous studies have investigated stiffness adaptations on surfaces with varied hardness. Reduced vertical leg displacements caused an increase in linear stiffness on softer surfaces, whereas increased leg displacements decreased stiffness on harder surfaces during running (Ferris et al., 1998). Also, rotational stiffness about the ankle and knee joint both increase during hopping on softer surfaces (Farley et al., 1998) and whilst running in softer midsole shoes (Baltich et al., 2015), compared to a harder surface and shoe condition. Although the shoe-surface interface used in these studies was flat, the soft conditions may produce some instability which is controlled through increasing stiffness levels.

Similar joint stiffness mechanisms have been observed regarding unpredictable perturbations. For example, hand stiffness increased in response to upper limb unpredictable perturbations (Burdet et al., 2001). Walking across a slippery or perturbing surface reduces range of motion and has been suggested to increase ankle and knee stiffness (Fong et al., 2005; Chmielewski et al., 2005). Moreover, Voloshina and Ferris (2015) found increased leg stiffness during running on an uneven treadmill surface.

In most unstable or perturbation experiments joint stiffness has been quantified by dividing the relative change in joint moment by the change in joint angle, applying a linear regression and taking

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http://dx.doi.org/10.1016/j.jelekin.2016.09.003
1050-6411/

the coefficient as the value of stiffness. The calculation does not comply with the true mechanical stiffness equation of Hooke's law and has been termed 'quasi-stiffness.' This is because it is applied across different joint components and may not alter elastic potential energy (Latash and Zatsiorsky, 1993). It does provide information about the resistance of a joint to deform and thus adaptations to shoe perturbations (Baltich et al., 2015). Ankle quasi-stiffness has been estimated in the foot-flat period during stance whilst walking (Gabriel et al., 2008; Kim and Lockhart, 2012) and running (Hamill et al., 2014; Kuitunen et al., 2002; Baltich et al., 2015). However, this is a relatively large phase of the gait cycle to take as a single stiffness measure which may obscure subtle changes. Sekiguchi et al. (2015) found ankle stiffness increased 2.6 times between the early and late phases of the second ankle rocker period of healthy adults' walking.

As mentioned, US are reported to increase muscle activation (Landry et al., 2010). However, some studies report no increases in muscle activation whilst walking (Nigg et al., 2006) or running (Sobhani et al., 2013), indicating the US tested were not challenging the neuro-muscular system enough to invoke a response. Plus, effects of US instability are short term, and a less predictable, more challenging training stimulus has been suggested to enhance training effects (Stöggl et al., 2010). A developed irregularly deforming midsole (IM) with unpredictable instability simulates the kinematics of uneven surfaces and may provide an enhanced training stimulus, requiring heightened joint stiffness and co-contraction strategies (Apps et al., 2015). Such a device may be particularly valuable for females because there have been a few reports of gender differences in levels of joint stiffness. Baltich et al. (2015) detected females further increased knee joint stiffness levels during running in softer midsole shoes, showing higher sensitivity than the males. Contrarily, Gabriel et al. (2008) found reduced ankle stiffness during the third ankle rocker in females during walking. These differences have been linked to females having greater joint laxity and reduced muscle strength; further challenging their joint stability and perhaps making them more susceptible to shoe instability.

Therefore, this study compares ankle and knee joint stiffness and ankle muscle co-contraction of females when walking and running in response to predictable and unpredictable shoe instability. It was hypothesised for walking and running:

1. US and IM would increase ankle and knee joint stiffness compared to a control shoe.
2. IM would further increase joint stiffness compared to US in the loading period of stance.
3. Increased ankle joint stiffness would be associated with increased muscle co-contraction.

2. Methods

2.1. Participants

Eighteen healthy females were recruited in this study (25.8 ± 2.5 years, 166.6 ± 4.3 cm, 61.8 ± 5.9 kg) Inclusion criteria required participants to be self-reported injury free, heel-toe runners, wear shoe size UK 5.5 ± 0.5 and have no previous experience with US. All participants took part in recreational exercise (5.5 ± 2.5 h/week). This study was approved by Liverpool John Moores research ethics committee and participants were informed of the aims of the study and gave written consent prior to testing.

2.2. Protocol

Participants walked and ran in three shoe conditions (Table 1): an US providing predictable instability, IM providing unpredictable instability and a regular shoe as a control (CS). Before testing participants were familiarised to each condition by treadmill walking and running for 90 s at 5 km/h and 8 km/hr respectively. In each shoe condition 20 successful overground trials were collected at a walking speed of 5 km/h (±5%) and running speed of 8 km/h (±5%). Before data collection, participants had practice trials to ensure they could land with their right foot on the force plate without targeting. The order of experimental locomotion was walk followed by run in the same shoe condition. The CS condition was always first to avoid potential crossover effect from US and IM, whose order was mixed between participants.

2.3. Data collection

Right lower limb kinematics were recorded at 500 Hz by an eight camera motion analysis system (Qualisys AB, Gothenburg, Sweden). The right thigh, shank and foot segments were defined by attaching reflective markers to the greater trochanter, medial and lateral femoral epicondyles, the lateral and medial malleoli, on the tip of the shoe and dorsal metatarsal heads 1 and 5. Tracking marker clusters were attached on the lateral side of the right thigh (4 markers) and shank (4 markers) on a rigid plate, and to the shoe

Table 1
Shoe conditions. Unstable shoe (US) top, irregular midsole shoe (IM) middle and control shoe (CS) bottom. IM and CS use the same shoe upper (Li Ning Fengchao TD, Li Ning Co, Beijing) and the developed midsole attached to the shoe upper by Velcro.

Shoe name	Abbreviation	Weight	Description	Image
Unstable	US	321 g	The Bubble Gym shoe (Li Ning, China) is characterised with a protruding rocker around the midfoot and smaller protrusions in the rearfoot and forefoot regions. The outsole configuration is aimed to create instability, but its fixed structure means it is predictable	
Irregular midsole	IM	218 g	Highly flexible rubber bags (hardness: 28 Asker C, thickness: 1.5 mm) at the rearfoot, midfoot and forefoot at 30%, 30% and 40% shoe length respectively. 42 ball bearings (12 mm diameter) and 7 cube shapes (height 15 mm, hardness: 85A Shore, TPU material) move independently throughout swing creating a different shoe-surface profile at every ground contact and thus unpredictable instability	
Control	CS	215 g	The midsole condition was modified from the original shoe with a stable, flat outsole. The width was cut and aluminium weights (5 g) were glued evenly to the midsole sides to replicate IM bags minimising mass and weight effects between CS and IM