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Transition from shod to barefoot alters dynamic stability during running

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A B S T R A C T

Introduction: Barefoot running recently received increased attention, with controversial results regarding its effects on injury risk and performance. Numerous studies examined the kinetic and kinematic changes between the shod and the barefoot condition. Intrinsic parameters such as the local dynamic stability could provide new insight regarding neuromuscular control when immediately transitioning from one running condition to the other. We investigated the local dynamic stability during the change from shod to barefoot running. We further measured biomechanical parameters to examine the mechanisms governing this transition.
Methods: Twenty habitually shod, young and healthy participants ran on a pressure plate-equipped treadmill and alternated between shod and barefoot running. We calculated the largest Lyapunov exponents as a measure of errors in the control of the movement. Biomechanical parameters were also collected.
Results: Local dynamic stability decreased significantly ($d = 0.41$; 2.1%) during barefoot running indicating worse control over the movement. We measured higher cadence ($d = 0.35$; 2.2%) and total flight time ($d = 0.58$; 19%), lower total contact time ($d = 0.58$; -5%), total vertical displacement ($d = 0.39$; -4%), and vertical impulse ($d = 1.32$; 11%) over the two minutes when running barefoot. The strike index changed significantly ($d = 1.29$; 237%) towards the front of the foot.
Conclusions: Immediate transition from shod to the barefoot condition resulted in an increased instability and indicates a worst control over the movement. The increased instability was associated with biomechanical changes (i.e. foot strike patterns) of the participants in the barefoot condition. Possible reasons why this instability arises, might be traced in the stance phase and particularly in the push-off. The decreased stability might affect injury risk and performance.

1. Introduction

Nowadays, running is enjoying increasing attention on both the recreational and elite level. It was traditionally considered as a key feature of athletic shoes to support and control the foot motion during running, thus reducing shock amplification, excessive strain magnitude and rate on muscles and ligaments of the longitudinal arch [1]. Barefoot running is increasingly present in the spotlight of the scientific and commercial fields. Further, all the more runners attempt to run barefoot or in barefoot-mimicking footwear [2]. However, previous research has reported conflicting findings. It has been suggested that some of the mechanical characteristics associated with barefoot running could induce fewer musculoskeletal injuries in runners [3], although recent studies failed to establish evidence on this argument [4]. Running economy has been shown to be a successful predictor of performance in distance running. While some studies found an improvement [5] in running economy in the barefoot condition, others were not able to identify any effects [6] and there are also studies that report a worsening [7] when barefoot compared to shod running.

Immediate transition from shod to barefoot running results in several biomechanical adjustments. Foot strike patterns change towards the fore of the foot [8], the ankle and knee joints exhibit higher and lower range of motion, respectively [9]. Cadence increases and step length decreases [9] while the arch of the foot also displays higher compression and recoil in the barefoot compared to shod condition [10]. These differences lead in altered posture and redistribution of moments in the lower extremities resulting in changes to limb stiffness, limb loading and whole body dynamics [11,12]. The central nervous system encounters variations during running, in both internal and external conditions, requiring adequate neuromuscular coordination [11]. This goal can be achieved through feedback- as well as predictive-based motor control using information about the "state" (i.e. displacement and velocity) of the system [13].

It has been often overlooked that the execution of a non-familiar

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Fig. 1. Marker placement on the participants' trunk: 1st, 6th, 10th, 12th thoracic vertebrae and 2nd lumbar vertebrae.

task from habitually shod runners, such as barefoot running may induce novel disturbances to the system. Such a task, could initiate control errors from deficits in the perception and processing of sensory information [11,12]. In addition, errors can arise from deficits in predicting the motor commands to deal with expected perturbations [11]. There is evidence that the rate of the navicular drop [14] and the magnitude of longitudinal arch compression increase during the stance phase while running barefoot [10]. This increase indicates effects on the sensory feedback information due to intrinsic changes in the state of muscles and ligaments of the longitudinal arch. Kelly et al. reported alterations in the activation level of the flexor *digitorum brevis* and *adductor halluces* while running barefoot, which resulted in a reduction in the longitudinal arch stiffness during the stance phase compared to shod condition. We can therefore argue that control errors can be introduced during barefoot running. These could derive from deficits in the perception of the arch state and conversion of this information into appropriate motor commands as well as from the increased mechanical demand on muscles and ligaments of the foot. Consequently, we could also expect alterations in intrinsic properties of the system such as the dynamic stability, which has never been investigated to date when comparing shod and barefoot conditions during running.

During locomotion, the local dynamic stability calculated using nonlinear time series analysis, can be adopted as a criterion for the occurrence of control errors [15,16]. The largest Lyapunov exponent (LLE), which quantifies how the system's states respond to very small perturbations −thus providing information regarding the neuromuscular control of the human system- has been often used to assess local dynamic stability during walking [15–18]. A previous study found a small effect of worsen stability in the vertical direction of movement when participants walked without shoes [19]. To date however, such approaches have only rarely been used during locomotion tasks such as running [20,21]. Alteration in the dynamic stability of the system could play a significant role when transition to the barefoot condition and constitute one mechanism contributing to the mentioned discrepancies in the literature regarding the effect of barefoot running on injury risk and performance [4,6].

The purpose of the current study was to investigate the local dynamic stability of the human system during an immediate alteration from shod to barefoot running. We anticipated that the reported intrinsic changes on the state of muscles and ligaments of the foot during the stance phase of barefoot running [10,14] would affect the demand of the neuromuscular system, initiating motor control errors. We hypothesised an increased instability after the transition from the shod to the barefoot running. In doing so, we measured several other biomechanical parameters to gain insights in the mechanisms governing this transition and examine how different parameters interact with one another.

2. Methods

Twenty healthy young adults (six female) were recruited to participate in the study (age 27.8 ± 5 years; mass 72.9 ± 11.9 kg; height 178.7 ± 8.1 cm). None of the participants had any musculoskeletal or neuromuscular impairments at the time of the measurements and at least six months prior to it. All of them walked and ran habitually shod in their daily life. The study was conducted in accordance to the university ethical committee guidelines.

The main setup of the study consisted of five high-speed video cameras (Flare 4M180-CCL, IO Industries Inc., Canada) operating at 190 Hz to record five reflective 10 mm-markers positioned on the spine. Namely, the first, sixth, tenth and twelfth thoracic as well as the second lumbar vertebrae were recorded (fig. 1). The video tracking was performed using dedicated software (Simi Motion 9.0.4, Simi Reality Motion Systems GmbH, Germany), while raw data were post-processed using custom algorithms (Matlab 2014b, Mathworks Inc., United States). Videos were synchronised with a pressure plate (120 Hz capturing frequency; FDM-THM-S, zebris Medical GmbH, Germany) integrated in the treadmill using an analog signal triggered by the video capturing software.

The participants executed randomly (based on computer-generated random numbers) two barefoot and two shod running trials at their preferred running speed, separated by a short resting period (60s). Each trial consisted of 40–60 s familiarisation time and 120 s capturing time. The individuals' preferred speed was determined while running shod,