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Fatigue and soft tissue vibration during prolonged running

Arash Khassetarash [a], Reza Hassannejad [a,*], Mir Mohammad Ettefagh [a], Vahid Sari-Sarraf [b]

[a] Department of Mechanical Engineering, University of Tabriz, Tabriz, Iran

[b] Department of Exercise Physiology, Faculty of Physical Education and Sport Sciences, University of Tabriz, Tabriz, Iran

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ABSTRACT

Muscle tuning paradigm proposes that the mechanical properties of soft tissues are tuned in such a way that its vibration amplitude become minimized. Therefore, the vibrations of soft tissue are heavily damped. However, it has been hypothesized that the ability of muscle tuning decreases with fatigue. This study investigated the changes in vibration characteristics of soft tissue with fatigue. Vibrations of the gastrocnemius muscle of 8 runners during a prolonged run protocol on a treadmill at constant velocity ($4\ \mathrm{ms}^{-1}$) were measured using a tri-axial accelerometer. The vibration amplitude is calculated using the Fourier transform and a wavelet-based method was used to calculate the damping coefficient. The results showed that: (1) the vibration amplitude in longitudinal direction increased with fatigue, which may be interpreted as the decreased muscle function with fatigue. (2) The amplitude increase percent strongly depended on the vibration frequency. (3) The damping coefficient of the gastrocnemius increased with fatigue. A 1-DOF mass-spring-damper model was used in order to validate the wavelet based method and simulate the observed phenomena.

1. Introduction

Soft tissues vibrate during running due to the shock loads transferred to the musculoskeletal system. The magnitudes of these loads can be 2–11 times body weight during running (Perry, 1983) or hopping (McNitt-Gray, 1991). Prolonged exposure of muscles to these loads could have negative effects such as pain experienced in lower leg muscles and loss of function (Cronin, Oliver, & McNair, 2004). However, short-term whole body vibration exposure, which is a forced vibration situation for muscles, has been shown to have positive effects, including increase in muscle force and knee extension (Ebid, Ahmed, Mahmoud Eid, & Mohamed, 2012; Ibrahim, Eid, & Moawd, 2014; Trans et al., 2009). During running, soft tissues are exposed to vibration for a relatively short time with higher intensity compared to aforementioned studies, however, in prolonged running this exposure happens repeatedly.

Many researchers have investigated the acceleration of soft tissue (Friesenbichlern, Stirling, Federolf, & Nigg, 2011; Boyer & Nigg, 2006; Enders, von Tscharner, & Nigg, 2012; Wakeling & Nigg, 2001). Since the frequency content of the ground reaction force (GRF), the input force to the musculoskeletal system in running, is in the range of the natural frequency of the soft tissue, it has been proposed that muscle activity adapts the mechanical properties of soft tissue so that its vibration amplitude become minimized (Nigg, 1997; Nigg & Wakeling, 2001) and it also has been shown that human body responds to the shock loads by activating the muscles (Wakeling, Nigg, & Rozitis, 2002). The mentioned studies, however, have

* Corresponding author at: Department of Mechanical Engineering, University of Tabriz, Tabriz 51666-14766, Iran.
E-mail address: hassannejhad@tabrizu.ac.ir (R. Hassannejad).

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considered only the non-fatigued condition. Fatigue can change the dynamic and vibration properties of human gait. Human body partly responds to fatigue by changing gait characteristics such as increased knee extension and decreased knee flexion (Mizrahi, Verbitsky, Isakov, & Daily, 2000), which these changes in fact, can affect the kinetic characteristics such as the GRF. Among kinetic characteristics, the GRF is the exciting force for the system of human musculoskeletal system during running. Regarding the effects of fatigue on the vibration properties of human gait, most of the papers have investigated the changes on the GRF, however, there is almost no agreement. Some studies have reported the increase in the GRF peaks with fatigue (Christina, White, & Gilchrist, 2001; Dickinson, Cook, & Leinhardt, 1985; Wikstrom, Powers, & Tilman, 2004), while some others have reported the decrease (Augustsson et al., 2006; Kellis & Kouvelioti, 2009; Nicol, Komi, & Marconnet, 1991). Researchers came to a hypothesis that the ability of human body in managing the ground collision decreases with fatigue, which leads to an increase in the GRF (Zadpoor & Nikooyan, 2012a, 2012b).

It has been speculated that the shock attenuation properties of soft tissues may decrease with fatigue, which leads to a decrease in damping characteristics (James, Scheuermann, & Smith, 2010). Based on an increase observed in vibration magnitudes, Friesenbichlern et al. hypothesized that the vibration damping mechanism of the triceps surae may reduced by fatigue (Friesenbichlern et al., 2011), however, they didn't calculate the damping coefficient of the vibration for non-fatigued and fatigued states of human running, a characteristic which is very important for mass–spring–damper models of human movement. To the best of our knowledge, no experimental study specifically has investigated the changes of the damping coefficient of soft tissue with fatigue. It has been reported that leg stiffness decreased (Fourchet, Girard, Kelly, Horobeanu, & Millet, 2015; Rabita, Couturier, Dorel, Hausswirth, & Le Meur, 2013) and the vibration amplitude of lower extremities increased (Friesenbichlern et al., 2011) with fatigue. If the lower extremities muscles can be modeled by a single-DOF mass–spring–damper model, and the GRF can be considered as the input of this system, a decrease in stiffness will result in an increase in vibration amplitude, but if the damping of the system increases simultaneously, it can lower the level of increase in vibration amplitude.

In the present study, in order to better recognize the fatigue-induced changes in vibration characteristics of soft tissue, vibrations of the gastrocnemius muscle in prolonged running are considered. By using a wavelet-based method (Enders et al., 2012) the changes in the damping coefficient of the gastrocnemius with fatigue is calculated. The hypotheses to test are:

(1) The vibration amplitude of soft tissue increases with fatigue.
(2) The damping coefficient of soft tissue increases with fatigue.

2. Methods

2.1. Experimental protocol

Eight male subjects (age: 26 ± 3.6, weight: 65 ± 12 kg, height: 175 ± 6 cm) volunteered in this study. Subjects gave their written consent to participate in the study and the study procedures complied with the Declaration of Helsinki and were approved by the University of Tabriz Research Ethics Board. All subjects were professional runners and rear foot strikers. They had no injuries in lower extremities over the last 6 months.

Prior to data collection, all subjects were given a 5 min warm up period. The subjects were asked to run on a treadmill at constant velocity of 4 ms^{-1}. The run was ended if (a) they reached to a high exhaustion level and was no longer able to run at the given speed or (b) the running distance was more than 10 km. The subjects ran 9.6 ± 1.14 km. Since the exhaustion level was different for each runner, therefore, similar to (Eskofier, Kugler, Melzer, & Kuehner, 2012), the participants were asked to rate their fatigue condition between 0 and 6 based on Table 1. The self-rated fatigue condition was used as a dimensionless fatigue time. After a meta-analysis, Zadpoor and Nikooyan suggested that in order to have comparable values in fatigue tests, the velocity and the fatigue level should be reported (Zadpoor & Nikooyan, 2012a, 2012b). The use of the treadmill and the self-rating fatigue condition was to assure of having a constant speed and a criterion of fatigue level.

2.2. Data collection

Two accelerometers were attached to each subject. A 3-axial accelerometer (Triaxial DeltaTron Accelerometer type 4504, weight: 14 g, frequency range 1 Hz–15 kHz) was attached to the gastrocnemius muscle and was oriented to be in the

Table 1
Self-rated fatigue condition.

Number	Meaning
0	Not at all
1	Little
2	Somewhat
3	Rather
4	Very
5	Extremely
6	Unable to continue