Journal of Biomechanics 93 (2019) 140–146

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Vibration settling time of the gastrocnemius remains constant during an exhaustive run in rear foot strike runners

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ARTICLE INFO

Article history:
Accepted 26 June 2019

Keywords:
Running
Fatigue
Soft tissue vibration
Ground reaction force

ABSTRACT

In this study, vibrations of human gastrocnemius during an exhaustive run protocol are considered for analysis. Previous studies have shown increased vibration intensity and damping coefficient within the soft tissue with fatigue. The question of this study was to investigate if the vibration settling time remains constant during a prolonged running. Eleven semi-professional middle/long distance runners ran to exhaustion on a treadmill with their preferred constant speed (4.29 ± 0.33 m/s) for 3873 ± 1147 m. Vibration of the gastrocnemius lateralis, electrical activity of the tibialis anterior and the gastrocnemius medialis along with ground reaction force (GRF) were recorded. The results demonstrated significant increase in impact peak and loading rate, and the frequency content of the impact, with no significant change in active peak of the vertical GRF. Fatigue resulted in increased vibration intensity, damping coefficient, and energy dissipation of vibration with no change in vibration settling time. Furthermore, peak acceleration significantly linearly ($R = 0.59$) increased as a function of running time. The mean frequency of muscle activity of the gastrocnemius medialis and the intensity of muscle activity in TA significantly decreased. The results suggest that constant vibration settling time might either be an objective for muscle tuning which is more pronounced in fatigued state or a passive by-product of muscle function in running. Further studies are needed to address this point.

1. Introduction

Running is one of the most prevailing recreational activities during the past decades. As running is becoming more popular, running injuries are increasing despite developments in sports sciences (Nigg et al., 2015). The way human body interacts with shock loads during running has long been assumed to affect running injury rate (Milner et al., 2006; Robbins et al., 1989; Schwellnus et al., 1990).

Muscle tuning paradigm portrays lower extremities muscles during running as an active vibrating system that can change its mechanical characteristics before ground contact based on the properties of input force (GRF) with a goal of minimizing muscle vibration (Nigg, 2001). Therefore, not being able to predict the mechanical properties of the input force during running might increase the risk of injury (Nigg et al., 2017) which emphasizes the importance of muscle tuning. It is also assumed that muscle fatigue during long distance running diminishes muscle tuning ability. For the vibrating system of lower extremities muscles, GRFs are considered as input, and muscle activity and vibration can be considered as the outputs. The changes in GRF (Christina et al., 2001; Girard et al., 2010; Nummela et al., 1994; Rabita et al., 2013) and muscle activities (Crozara et al., 2015; Nummela et al., 1994), and muscle vibration (Friesenbichler et al., 2011; Khassetarash et al., 2015b) associated with prolonged running have been previously investigated.

The magnitude and frequency of the GRF, as the input force, are important when considering soft tissue vibration. The vertical component of the GRF (VGRF) in running contains two peaks; the first and the second peaks are called "impact peak", and "active peak" respectively, and the rate of impact peak development is known as "loading rate". There are somehow controversial results regarding the effect of fatigue on the impact and the active peak of the GRF; while some studies reported increase in GRF peaks with fatigue (Christina et al., 2001; Wikstrom et al., 2004), others reported decrease (Dickinson et al., 1985; Rabita et al., 2011). However, the loading rate seems to increase with fatigue (Christina et al., 2001; Dickinson et al., 1985).

It has been reported that lower extremities vibration intensity (Friesenbichler et al., 2011; Khassetarash et al., 2015b) and their

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https://doi.org/10.1016/j.jbiomech.2019.06.026
0021-9290/

damping characteristic (Khassetarash et al., 2015b) increases with fatigue, however, the underlying mechanical mechanisms involved in this process is not known. It has been hypothesized that muscle tuning decreases as fatigue develops (Friesenbichler et al., 2011; James et al., 2010, 2006), meaning that the vibrating system of muscles fails to track its objective function in minimizing muscle vibration. However, vibration settling time might also be an important characteristics of muscle vibration, linked to damping properties of the soft tissue, and shows the amount of time muscles were exposed to vibration.

In control theory, settling time (TS) of a system is defined as the time needed for the response curve to settle down to a predefined (usually 2– 5% of maximum intensity) value (Ogata, 2010). TS is a criterion showing how fast a system responds to a certain disturbance. It usually depends on the stiffness and damping properties of the system, but the properties of input force also play an important role in TS, especially in a nonlinear vibration such as soft tissue vibration. For a closed loop control system, the controller can be set to track a certain criterion. This view has been implemented in mass-spring-damper models of human running (Liu and Nigg, 2000) to mimic muscle tuning (Zadpoor and Nikooyan, 2010), and has led to qualitatively agreeable results in the effects of fatigue on muscle vibration (Khassetarash and Hassannejad, 2015; Nikooyan and Zadpoor, 2012).

However, as a vibrating system, stiffness and damping of soft tissue and their temporal change during ground collision could modulate the resultant vibration. Increased vibration intensity accompanied by increased damping coefficient of vibration suggests that the soft tissue vibration settling time, initiated by ground contact, tends to remain constant. Minimizing the vibration exposure time by keeping a constant TS might be an objective function of muscle tuning to minimize the damage the soft tissue is undergone. This objective might be more pronounced over a course of fatiguing run to minimize the cumulative damage to the soft tissue. The purpose of this study is, therefore, to investigate the effects of an exhaustive run on vibration characteristics of lower body soft tissue, and the hypothesis to test is:

(H) Vibration settling time within the gastrocnemius remains constant during an exhaustive run.

2. Materials and methods

2.1. Participants

Eleven male runners (height: 174.3 ± 4.63 cm, weight: 65.9 ± 9.86 kg, age: 32.7 ± 9.94 years) with no history of lower extremities injury during the past six months volunteered in this study. All participants were semi-professional middle/long distance runners (personal best over 3000 m: 9 min and 57 s ± 38.5 s) and habitually rear foot strikers. The strike pattern was assessed visually using high-speed videos taken from the sagittal plane during running. The participants gave their written consent to participate and the test procedure compiled with the Declaration of Helsinki and was approved by The University of Tabriz Ethics Board.

2.2. Data recording

2.2.1. Vibration data

Prior to data collection, each participant was given a five-minute warm up period. A tri-axial accelerometer (Triaxial DeltaTron Accelerometer type 4504, mass: 14 g, frequency range 1 Hz to 15 kHz) was attached to the muscle belly of the lateral gastrocnemius using medical adhesive (tightened by rolling around the calf) tape and it was aligned to record vibration in longitudinal, medio-lateral and anterio-posterior directions. Gastrocnemius was chosen for vibration measurement as one of the large muscles in the leg to minimize the effects of accelerometer's mass, and under the assumption that the relationship between GRF and muscle vibration is more direct. A uniaxial accelerometer (B&K type 4507, mass: 4 g, frequency range 1 Hz to 15 kHz) was attached to the lateral malleolus to determine ground contact. Vibration data was recorded at 2000 Hz using a 12-bit data acquisition system (National Instrument, NI cDAQ-9172). The participants were asked to run on a treadmill to volitional exhaustion with their preferred constant speed. The runners were advised to select a speed that required a high level of effort to finish the protocol. The selected speed was confirmed by their mentors. Strong verbal encouragement was given by the participant's mentor at the end of the run to encourage the subject to run until the exhaustion. The vibration data was continuously recorded from the start to the end of the run.

2.2.2. Muscle activity

Muscle activity was measured using ME6000 Biomonitor EMG System (revision MT-M6T16-0). EMG recordings were made using a pair of surface electrodes (silver-silver chloride, 55 mm) placed over the tibialis anterior muscle (at proximal one third of the line between the tip of the fibula and the tip of the lateral malleolus) and over the gastrocnemius medialis muscle of the dominant leg. A reference electrode was placed over the medial malleolus. Surface electrodes were secured onto the shaved and cleaned skin above muscles. EMG signals were collected continuously from the beginning to the end of the run at a sampling frequency of 2000 Hz.

2.2.3. Ground reaction force

The participants were instructed to run at their comfortable speed (performable even after the fatiguing run) on a 15-m running path instrumented by a force plate (Type 9260AA6, Kistler, Switzerland, 2009, dimensions: $600 \times 500 \times 50$ mm) in the middle. To prevent the effect of targeting, the path was covered in a way that the participant could not know the place of the force plate. The participant's performance on the sagittal plane was recorded by a typical camera (SONY FS5) at 800 Hz. One set of the GRF data was collected before running on the treadmill and regarded as pre-exercise GRF. The other set was collected after running on the treadmill and regarded as the post-exercise GRF. The participants were asked to perform four successful trials on force plate. The number of steps were determined to be performable within 2 min. It has been shown that muscle's ability to produce tension increases almost exponentially as soon as the termination of exercise (Froyd et al., 2013). Therefore, we only considered GRF data that was performed within two minutes following the termination of the treadmill run. The participant's foot strike pattern was observed from the video camera recording the movements in the sagittal plane. GRF data was recorded at the rate of 2000 Hz and then lowpass filtered using a 4th order Butterworth filter with cut-off frequency of 50 Hz.

2.3. Vibration data processing

2.3.1. Synchronized averaging

Lateral gastrocnemius vibration data in longitudinal direction is considered for analysis. This exhaustion time differed between participants, therefore, to have a comparable data between participants, the time to exhaustion was divided into ten equal intervals (88.0 ± 25.82 s). Regarding the cyclo-stationary behavior of human running, five strides at the end of each interval were synchronized averaged to form a representative vibration for each time interval. This synchronized average for the first interval was calculated using the first five strides. An example of the mean acceleration signal with five consecutive strides has been illustrated in Fig. 1.

2.3.2. Settling time and damping

The time interval within which the muscle is vibrating after each heel strike is defined as the time between the maximum vibration intensity and the time that the intensity reaches 10% of its maximum magnitude, and this period is regarded as TS. The vibration data is contaminated with moving artifacts (even after a high pass filtering), therefore, the 10% criterion was chosen instead of 2 or 5% to ensure the relevancy of the calculated parameter. However, a correct calculation of vibration intensity might be performed using time-frequency analysis. It has been previously shown that muscle vibration during running consists of a combination of several vibration modes (Khassetarash et al., 2015a). Therefore, to calculate the vibration intensity, one might consider the cumulative effect of each vibration mode. In order to do so, a wavelet analysis method has been introduced to determine the overall power of vibration with different frequencies (Enders et al., 2012). Since the practical frequency bandwidth of vibration data in this study is <100 Hz, similar to (Khassetarash et al., 2015b), a filter-bank of 10 nonlinearly scaled Cauchy-type wavelets (center frequencies ranging from 6 to 130 Hz) was used for time-frequency analysis (Table 1). A typical representation of the raw vibration signals and the cumulative power of all vibration modes are shown in Fig. 2. Damping coefficient of vibration was also calculated based on the method by (Enders et al., 2012). In order to compare the effect of change in damping coefficient, the energy dissipation was also calculated based on the following equation previously explained by (Khassetarash et al., 2015a).

$$\frac{E}{m} = 2D\int_{t_0}^{t} \dot{y}^2 dt$$

where E is the energy dissipated via damping in Joules, m is the muscle mass in kg, D is the damping coefficient in s^{-1}, and $\dot{y}$ is the velocity of vibration in $m\cdot s^{-1}$.

Finally, Stride frequency was defined as the inverse of the time difference between two consecutive touchdowns, and stride length was determined as running velocity divided by stride frequency.

2.3.3. Muscle activity

As previously mentioned, muscle activity was recorded using EMG from the medial gastrocnemius (GA) and the tibialis anterior (TA). A 4th order bandpass Butterworth filter with cut-off frequencies of 20 and 500 Hz was applied on the EMG data. The same procedure (Section 2.3.1) as for vibration data was performed on the EMG data to determine the time points of interest. The heel strike was determined by the synchronized accelerometer data and the EMG data was analyzed for a time window of 250 ms after the heel strike. The magnitude of muscle activation was calculated in terms of root mean square (RMS). A Fourier transform then performed on autocorrelation function of each EMG data to transform the time domain signal to the frequency domain. A mean frequency (MF) then defined to determine the frequency around which the power of EMG signal is concentrated within a frequency bandwidth corresponding to 95% of the power. RMS and MF of the EMG was analyzed to capture any differences between pre and post exercise states.

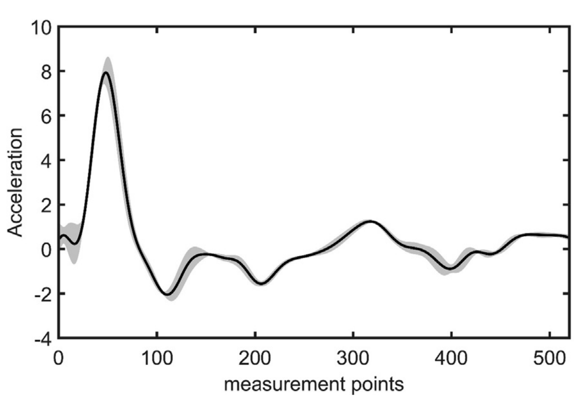

Fig. 1. An example of measured acceleration as the mean of five consecutive stride (solid line) and the corresponding standard deviation (gray shaded area).

Table 1
Properties of the wavelets with scaling factor of s = 0.7.

Wavelet #	Center frequency [Hz]	Time resolution [ms]	Bandwidth [Hz]
1	1.72	260	4
2	6.07	140	6
3	12.99	100	8
4	22.41	80	10
5	34.31	0	12
6	48.66	55	15
7	65.44	40	17
8	84.63	33	19
9	106.21	30	23
10	130.17	25	28

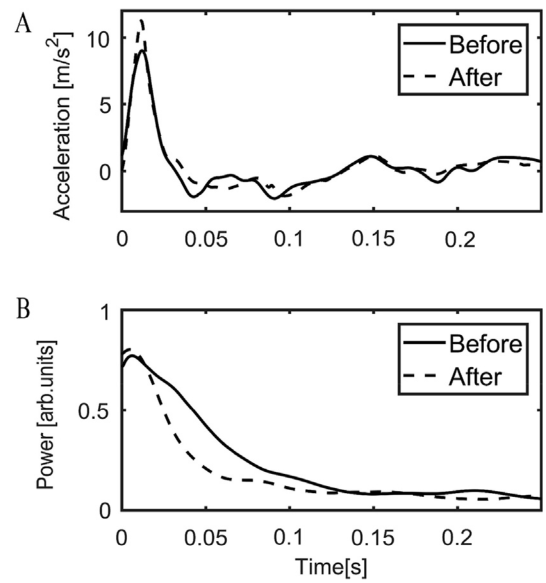

Fig. 2. (A) Raw acceleration data from the gastrocnemius lateralis at the beginning and at the end of treadmill run. (B) Cumulative power of the whole vibration modes in signals of (A) at the beginning and at the end of treadmill run.

2.3.4. Ground reaction force

The GRF data was low-pass filtered with a 4th order Butterworth filter with cut-off frequency of 30 Hz. Four successful trials for each subject were synchronized averaged to achieve a more reliable representative GRF. The impact and the active peak of the vertical component of the GRF (VGRF) along with its loading rate (defined as the average slope between heel-strike (0.1 body weight) and the impact peak) were analyzed for pre and post exercise conditions. Furthermore, the frequency content of the impact force was calculated by fitting a sinusoidal wave to the impact part of VGRF. A representative of GRF for pre and post exercise conditions is shown in Fig. 3.

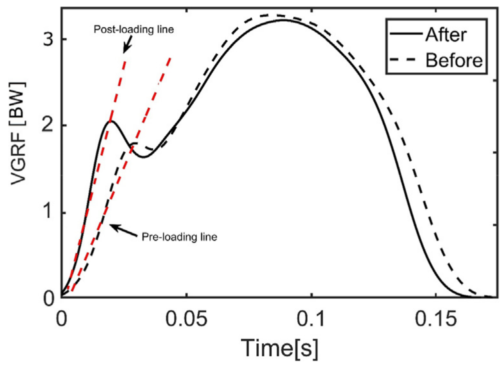

Fig. 3. A sample of filtered vertical ground reaction force before and after the treadmill run. Loading rates are identified.

2.4. Statistical design and analysis

As previously shown, fatigue has a large effect ($d > 1$) on vibration intensity of gastrocnemius (Khassetarash et al., 2015b). Hence, for a large effect size (Cohen's $d = 1$) and a significant level of $\alpha = 0.05$, a minimum of 10 participants is required to achieve a statistical power of $1 - \beta = 0.8$. Values are presented as mean ± standard deviation throughout the text. All variables were analyzed for normality and homogeneity of variances. Single factor (time) repeated measures ANOVA was used to explore significant differences in vibration intensity. Bonferroni's post-hoc test was applied if a significant difference was detected by ANOVA. A linear regression analysis was conducted to evaluate the relationship between TS and normalized running time, and between peak acceleration and normalized running time. Paired sample T-test was used to determine significant differences in RMS-EMG, mean EMG frequency, running velocity, stride length, and stride frequency, damping coefficient, and energy dissipation before and after the exhaustive run.

3. Results

The participants ran 3.873 ± 1.147 km (average ± SD.) with self-selected constant speed of 4.29 ± 0.33 m/s and time to exhaustion of 15 min and 3 s ± 1 min and 46 s.

3.1. VGRF

Only eight participants were able to finish four successful trials of the GRF measurement within 2 min following running termination. Their approaching speed was 3.54 ± 0.17 m/s before, and 3.24 ± 0.25 after the treadmill run. A significant increase was observed in impact peak of the VGRF ($p < 0.01$) and VLR ($p < 0.05$), while the active peak remained unchanged. Furthermore, a significant ($p < 0.05$) increase in the frequency of the impact peak was also observed. A summary of results is written in Table 2.

3.2. Vibration & EMG

On average, TS after each touchdown remained constant from the beginning to the exhaustion (Fig. 4**A**). ANOVA demonstrated no significant changes in either of the stages of running ($F = 0.0921$, $p = 0.9999$). Also, the linear regression did not show any relationship between TS and running time ($R = 0.004$). The scatter plot is shown in Fig. 5**A**. Vibration intensity in terms of normalized peak acceleration (normalized to the highest acceleration for each subject) increased (Fig. 4**B**) with fatigue development ($F = 7.34$, $p < 0.001$) and became significant after time point # 7 (e.g. 70% of time to exhaustion). Linear regression analysis also

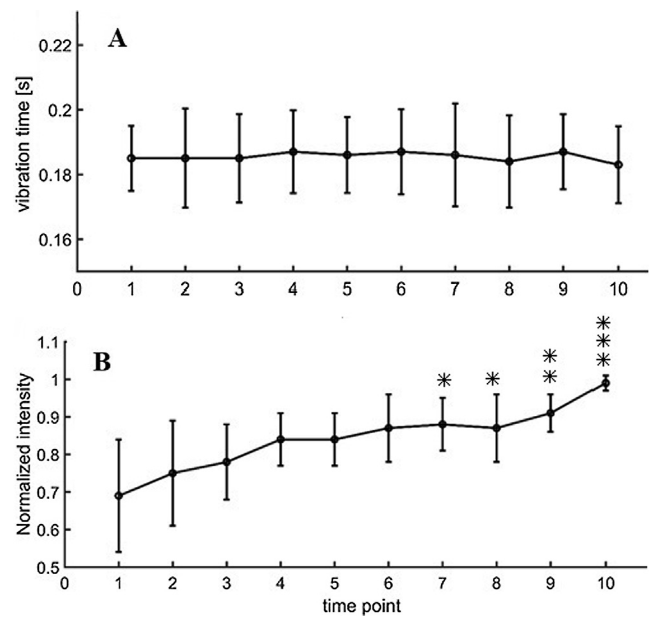

Fig. 4. (A) Vibration settling time (TS) after each ground contact versus non-dimensional time. (B) Non-dimensional peak acceleration versus non-dimensional time.

Table 2
A summary of results for vibration, EMG, and GRF data for pre and post exercise conditions. Data are shown in Mean ± SD. Significant differences are identified by asterisk (*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$).

Variable		Before	After	Percent difference %	*p*-value	Cohen's d
Vibration	Settling time [s]	0.185 ± 0.010	0.183 ± 0.012	−0.880	0.37	–
	Normalized vibration intensity	0.69 ± 0.15	0.99 ± 0.02	+29.80	0.0002^{***}	3.44
	Stride Frequency [Hz]	2.97 ± 0.14	2.95 ± 0.21	−1.09	0.35	–
	Stride length [m]	1.41 ± 0.11	1.42 ± 0.12	+0.76	0.34	–
	Damping coefficient [s^{-1}]	10.9 ± 2.51	12.6 ± 2.67	+15.5	0.018^{*}	0.65
	Energy dissipation [J/kg]	0.025 ± 0.029	0.043 ± 0.042	70.6	0.01^{*}	0.49
EMG	GA-MNF	145.2 ± 9.70	138.9 ± 12.95	−4.91	0.0212^{*}	0.56
	GA-RMS	0.79 ± 0.106	0.83 ± 0.112	+3.79	0.1813	–
	TA-MNF	140.3 ± 11.9	136.1 ± 11.2	−3.10	0.0540	–
	TA-RMS	0.89 ± 0.14	0.65 ± 0.21	−55.40	0.0105^{*}	1.35
VGRF	Impact peak	1.96 ± 0.32	2.54 ± 0.64	+28.20	0.0014^{**}	1.21
	Active peak	2.54 ± 0.64	2.71 ± 0.26	+1.40	0.3110	–
	Loading rate	86.4 ± 32.2	164.7 ± 96.3	+80.00	0.0100^{*}	1.21
	Impact peak frequency [Hz]	14.8 ± 0.76	16.9 ± 0.55	+14.25	0.019^{*}	3.20

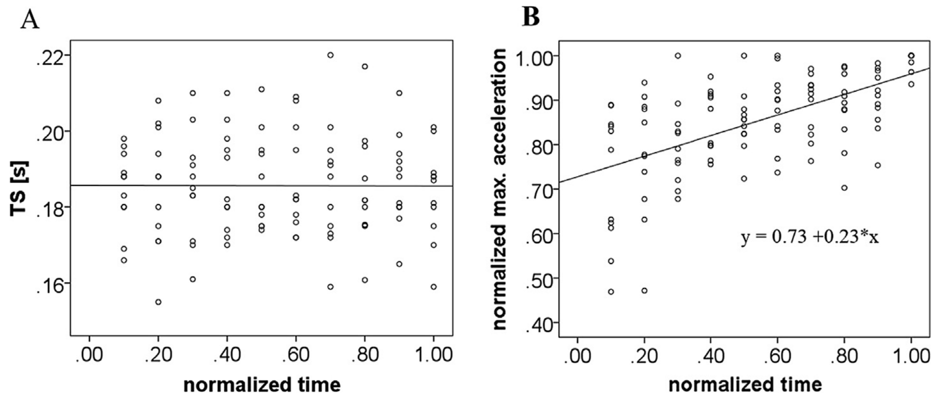

Fig. 5. Scatter plots and the linear regression. (A) Vibration settling time (TS) after each ground contact versus non-dimensional time. (B) Non-dimensional peak acceleration versus non-dimensional time.

demonstrated a significant linear relationship between normalized time and normalized peak acceleration ($R = 0.59$) as shown in Fig. 5**B**. Damping coefficient of vibration significantly ($p < 0.05$) increased up to 15.5%, and the energy dissipation significantly ($p < 0.05$) increased by 70.6% in fatigued state compared to the baseline (Table 2). No significant change in stride frequency and stride length were detected. A significant decrease with very large effect size in muscle activity in terms of RMS was observed for TA ($p < 0.05$), while no significant change occurred in the same parameter for Gastrocnemius (GA) activity. Mean frequency of the gastrocnemius EMG significantly ($p < 0.05$) decreased with medium effect size ($d = 0.56$), while no significant decrease observed for TA mean frequency. All participants reached at least 2.5% decrease in GA's mean frequency at the end of the run. A summary of the results is presented in Table 2.

4. Discussion

Analysis of EMG signals in GA revealed a shift to lower frequencies which has been regarded as an indicator of muscle fatigue (Cifrek et al., 2009; Sadoyama and Miyano, 1981), however, it could also be a result of modification in EMG level. Regarding muscle vibration, our hypothesis was that the period during which the muscle is exposed to vibration remains constant during an exhaustive run. The ANOVA and the linear regression analysis demonstrated no significant relationship between normalized running time and TS, resulting in acceptance of our hypothesis.

Peak acceleration gradually increased (with a very large effect size (Table 2)) as exercise continued, reaching to the highest magnitude at the exercise termination point. The increase in vibration intensity has been previously reported (Friesenbichler et al., 2011; Khassetarash et al., 2015b), however, in those studies, the GRF has not been measured. From mechanical vibration view, the change in the GRF, as an input to the human musculoskeletal system during running (Nigg, 2001), could modulate the vibration characteristics of the muscles. The peak acceleration of the GA is partly a result of the impact peak of the VGRF. Elevated impact peak of the VGRF (Table 2) was accompanied by increase in peak vibration intensity. It appears that increased impact peak primarily affected the vibration intensity just after the touchdown, however, this elevated intensity was later accompanied by increased damping coefficient and energy dissipation (Table 2). Therefore, even in the presence of higher impact loads, soft tissue vibration was heavily damped, and the vibration energy was dissipated in larger magnitude in fatigued state. This may suggest increased muscle activity to attenuate the shock loads, however, the EMG data did not support any significant elevation in GA muscle activity. Therefore, it remains unclear whether the observed increase in damping and constant TS is an active function of muscles or just a passive by-product of muscle function.

One parameter that could potentially contribute to vibration exposure within the muscle is stride frequency, as higher stride frequency would add up to more cumulative vibration to run a given distance. It seems that the intensity and duration of running can change how runners adapt their stride frequency when fatigued. A 1-hour high intensity running resulted in decreased stride frequency (Hunter and Smith, 2007), shifting towards the metabolically optimal stride frequency where the oxygen cost is minimized. On the other hand, it has been reported that in ultra-long distances (more than a marathon), runners tend to adapt a higher stride frequency (Degache et al., 2013; Morin et al., 2011). However, in our study, we did not detect any significant changes in stride frequency which was predictable since a short running protocol such as the present study would not be as mechanically demanding as an ultramarathon. It should be noted that the origin of fatigue depends on the type of exercise as a short running such as the present protocol might be expected to produce more peripheral fatigue, however, the contribution of factors distal to neuromuscular junction (central fatigue) increases in longer running protocols (Martin et al., 2010). Furthermore, the origins of exhaustion might be more physiological than mechanical in short duration-high intensity running. Therefore, soft tissue vibration might be affected differently in longer distances or mechanically demanding protocols such as downhill running (Ehrström et al., 2018), especially, if the central fatigue is elevated, the response of soft tissue to the exciting force (GRF) might shift to a more mechanical response than a biomechanical. The aforementioned speculation, however, requires further evaluations.

Within the group, some participants adopted higher stride frequency at the end, but some others did not change their stride frequency or even decreased their stride frequencies. Therefore, a relatively constant TS and stride frequency indicates that the cumulative vibration dose for a specific time at the beginning and at the termination of run remained constant.

The results of the current study, therefore, demonstrated that despite increase in peak vibration intensity, the settling time remained constant. This fact implies that the damping properties, or in better word, the energy dissipation capability of muscle increases as exercise prolonged which has been reported in our previous study (Khassetarash et al., 2015b) as well. It is assumed that the central nervous system fine-tunes the mechanical properties of muscles to decrease the intensity of vibration within the soft tissues (Nigg, 2001; Wakeling et al., 2003, 2002, 2001) which has been defined as the paradigm of muscle tuning (Nigg, 2001). It has been put forth that muscle tuning capability decreases with fatigue resulting in increased vibration intensity (Friesenbichler et al., 2011; James et al., 2010, 2006). In vibration exposure, the intensity of vibration is only one important factor, while the other factor is the exposure time (Griffin, 1990). Even though the situation in running is not whole-body vibration, the concept of forced vibration is still applicable. The results of current study suggest that either there is another objective for muscle tuning, which is keeping a constant settling time that is more pronounced with fatigue, or the observed phenomenon is just a by-product of muscle function.

4.1. Limitations

The participants in this study used their own footwear and apparel during the protocol. Previous studies have shown the effect of these equipment on muscle vibration (Giandolini et al., 2017) that might limit the conclusion of the current study. However, since the study design was within subject, the aforementioned limitation was minimized. Furthermore, despite selecting a relatively homogenous group of runners, and using a self-selected pace, the participants might have applied different pacing strategy to keep the constant speed, and the fact that the force loss within the soft tissue was not measured, limits the answer if the pacing strategy produced different levels of fatigue for the participants.

There was a significant ($p < 0.01$) difference between treadmill and over-ground running speeds. Also, a significant ($p < 0.01$) difference was detected for over-ground running speed before (3.54 m/s) and after (3.24 m/s) treadmill run. As it has been previously shown (Keller et al., 1996), the VGRF increases linearly with speed of running up to 3.5 m/s. However, for the speeds more than 3.5 m/s, the VGRF peak seems to reach a plateau with no significant effect of speed. On the other hand, vertical loading rate increases almost linearly with the speed (Keller et al., 1996). Therefore, since the participants ran on significantly higher speed on treadmill than over-ground, the loading rates on treadmill run is expected to be higher than that reported for over-ground. As a conclusion, if the over-ground running speed was the same as on the treadmill, the VGRF as an input force, would have had approximately the same magnitude as reported in Table 2 with a higher frequency. This difference, however, cannot change the general discussion made about the change in input force and the concomitant change in muscle vibration.

Even though it has been shown that the kinematic parameters of running do not differ in over-ground and treadmill (Firminger et al., 2018), since the conditions on the treadmill might differ from over-ground running, specially the surface hardness, caution should be made when interpreting the results of this study.

One limitation of this study was that the GRF measurement did not occur immediately after the termination of exercise which will underestimate the effects of fatigue. This study was conducted on semi-professional middle/long distance runners. It is possible that these runners have adopted a protective mechanism by increasing the amount of energy dissipation within the soft tissue, therefore, the situation might be different for recreational runners.

5. Conclusion

In short, this study demonstrated that despite increase in vibration intensity, the settling time of the soft tissue vibration remained constant during an exhaustive run. Despite increase in damping coefficient and energy dissipation of vibrations, the EMG data did not reveal significant increase in gastrocnemius activity. Therefore, it remains unclear whether the observed "constant vibration settling time" is actively produced by muscle tuning or is just a passive by-product of muscle function.

Declaration of Competing Interest

We certify that there is no conflict of interest with any financial organization regarding the material discussed in this study.

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