JOURNAL OF SPORTS SCIENCES
2021, VOL. 39, NO. 4, 439–445
https://doi.org/10.1080/02640414.2020.1824366

Routledge
Taylor & Francis Group

SPORTS MEDICINE AND BIOMECHANICS



# High vibration frequency of soft tissue occurs during gait in power-trained athletes

Chia-Hsiang Chen[a], Wen-Wen Yang[b], Yi-Ping Chen[c], Vincent Chiun-Fan Chen[d], Chiang Liu[e] and Tzyy-Yuang Shiang[c]

[a]Office of Physical Education, National Pingtung University of Science and Technology, Pingtung, Taiwan; [b]Department of Sports Medicine, China Medical University, Taichung, Taiwan; [c]Department of Athletic Performance, National Taiwan Normal University, Taipei, Taiwan; [d]Engineering Science, Loyola University Chicago, Chicago, IL, USA; [e]Graduate Institute of Sports Equipment Technology, University of Taipei, Taipei, Taiwan

**ABSTRACT**

Muscles serve as a critical regulator of locomotion and damping, resulting in changes of soft tissue vibration. However, whether muscle fibre compositions of different individuals will cause different extents of soft tissue vibration during gait is unclear. Therefore, this study investigated the differences in lower extremity vibration frequencies among power-trained and non-power-trained athletes during walking and running. Twelve weightlifting athletes were assigned to the power-trained group and twelve recreational runners were assigned to the non-power-trained group. Accelerometers were used to detect soft tissue compartment vibration frequencies of the rectus femoris (RF) and gastrocnemius medialis (GMS) during walking and running. Results indicated that power-trained athletes, as compared to the non-power-trained, induced significantly ($p < 0.05$) higher vibration frequencies in their soft tissue compartments during walking and running. This suggests that power-trained athletes, who have higher ratios of fatigable fast-twitch muscle fibres, may have induced higher soft tissue compartment vibration frequencies. As a result, there is a likelihood that power-trained athletes may recruit more fatigable fast-twitch muscle fibres during muscle tuning, causing dysfunctions during prolonged exercises.

**ARTICLE HISTORY**
Accepted 12 September 2020

**KEYWORDS**
Training; lower extremity; muscle fatigue; oscillation; sensor

## Introduction

Accelerometer-derived vibration frequencies of soft tissue compartments provide valuable information of internal responses due to external stimuli during dynamic exercises (Islam et al., 2012; Khassetarash et al., 2015). A study reported that data regarding the vibration frequencies of soft tissue compartments could be used to understand the composition of muscle fibres during muscle contraction. The study showed that the contraction of muscles containing a larger portion of type II muscle fibres resulted in higher vibration frequencies of soft tissue compartments (Mealing et al., 1996). Additionally, adjustment of the vibration frequencies of soft tissue compartments by muscles is essential to prevent the frequency from being too close to the natural frequency and can minimize the impact-inducing vibration of soft tissues (Martinez et al., 2019; Wakeling et al., 2003; Wakeling et al., 2002). In static situations, soft tissues have a constant vibration frequency. However, in dynamic situations, the vibration frequency of soft tissue compartments depends on external stimuli, such as exercise intensity (Khassetarash et al., 2019), strike pattern (Enders et al., 2014), and shoe material (Wakeling et al., 2003) that induce different levels of impact to the soft tissues through the vibrations (Wakeling & Nigg, 2001). Continuous measurements of the soft tissue compartment vibration frequency by applying accelerometer-based sensors attached to the skin of the muscle belly (Islam et al., 2012; Trama et al., 2019) can accurately reflect internal conditions and external demands during gait.

Vibration frequencies of soft tissue compartments are affected dynamically by different exercise intensities during movements because of muscle activation adjustments (Boyer & Nigg, 2004; Wakeling et al., 2001). For example, compared with walking, running has greater effects on the soft tissue compartment vibration frequencies because it elicits greater muscle activation and acceleration. In addition to the demand of movement intensities, to prevent the frequency from being too close to the natural frequencies, the target muscles of the lower extremity, such as the quadriceps and gastrocnemius, must be activated to reduce soft tissue vibrations by adjusting stiffness (Nigg & Liu, 1999). This process is called muscle tuning (Wakeling et al., 2003; Wakeling, Pascual et al., 2002). Muscle activation is a critical factor regulating the vibration frequencies of soft tissue compartments during dynamic movements.

Studies have indicated that external stimulation alters the recruitment pattern of muscle fibre types (Wakeling et al., 2001; Wakeling et al., 2002). Furthermore, it has been reported that fast-twitch muscle fibres (type II fibres), which can generate force in a very short period of time through anticipatory muscle activation or stretch reflex to control soft tissue vibration at heel strike, may be the key regulator of soft tissue vibration (Friesenbichler et al., 2011; Wakeling et al., 2002). These findings raise the question as to whether the ratio of muscle fibre types affects the vibration frequencies of soft tissue compartments during repeated impact movements.

**CONTACT** Tzyy-Yuang Shiang tyshiang@gmail.com Research Chair Professor Department of Athletic Performance, National Taiwan Normal University, Taipei, 11677, Taiwan

The first two authors contributed equally.

Although it has been suggested that muscle activation and lower extremity stiffness may influence the vibration frequencies of soft tissue compartments, no study has investigated the influence of muscle fibre type compositions on soft tissue compartment vibration frequencies during continuous movements. To fill this research gap, the present study investigated the vibration frequencies of lower extremity soft tissue compartments during different movement intensities among power-trained and non-power-trained athletes. Power-trained athletes generally exhibit a specialized level of athletic participation and undergo strength-related training for extended periods. Such athletes possess more fast-twitch muscle fibres than non-power-trained individuals (Harber et al., 2002; Serrano et al., 2019). This difference in muscle fibre type composition may cause distinct effects on the soft tissue compartment vibration frequencies in the two groups. Under the assumption that motor units will form task groups that can be recruited based on different kinematic conditions (Loeb, 1985; Von Tscharner & Goepfert, 2006; Wakeling & Rozitis, 2004; Wakeling et al., 2006) and that slow-twitch and fast-twitch muscle fibres will be recruited in both power-trained and non-power-trained athletes during different gait speeds (Hodson-Tole & Wakeling, 2009; Lee et al., 2013; Wakeling et al., 2006), this study proposed the following hypotheses: (1) The lower extremity soft tissue compartment (rectus femoris, RF and gastrocnemius medialis, GMS) vibration frequencies acquired from power-trained athletes are significantly higher than those acquired from non-power-trained athletes. (2) The RF and GMS vibration frequencies of both power-trained and non-power-trained athletes acquired during running are significantly higher than those acquired during walking.

## Materials and methods

### Participants

Twenty-four male students from the University of Taipei were recruited for this study and were divided into power-trained (n = 12) and non-power-trained groups (n = 12). Those who had any musculoskeletal or neurological disorders of the lower extremities during the previous 6 months were excluded from this study. Their exercise type, duration, frequency and intensity for the past 3 months were also collected. We have confirmed that all participants were heel strikers to minimize the effect of different running patterns. The training conditions and body composition of the participants are presented in Table 1. According to earlier studies (Fry et al., 2003; Serrano et al., 2019), weightlifters have a larger portion of type II muscle fibres and a lower portion of type I muscle fibres, while runners have just the opposite composition (Harber et al., 2002). The participants in the power-trained group were members from the weightlifting team of the academy. Their highest weightlifting performance levels in a competition were 108.0 ± 17.6 kg snatch and 143.2 ± 23.2 kg clean jerk. For the weightlifters, a minimum 3-day rest period was arranged before running measurements. The participants in the non-power-trained group were recreational runners (running as their main sport and habit). This study was approved by the medical research ethics committee of Taipei Medical University and all participants completed an informed consent form in accordance with the Declaration of Helsinki.

Table 1. Body composition and training conditions of the participants.

| | Power-trained group (n = 12) | Non-power-trained group (n = 12) |
|---|---|---|
| Body composition | | |
| Height (cm) | 165.6 (10.2) | 171.1 (5.2) |
| Weight (kg) | 77.3 (15.2) | 68.6 (5.2) |
| BMI | 26.6 (2.7) | 23.5 (2.2)* |
| Circumference of thigh (cm) | 55.1 (5.4) | 55.4 (2.5) |
| Skinfold thickness of thigh (mm) | 10.1 (2.2) | 14.7 (4.8)* |
| Circumference of shank (cm) | 38.4 (1.5) | 38.0 (2.1) |
| Skinfold thickness of shank (mm) | 10.1 (2.7) | 9.67 (2.8) |
| Training conditions | | |
| Frequency (day/week) | 5 | 3–5 |
| Time (min) | 120–150 | 30–60 |
| Intensity | 70–100% | Free |
| Type | Snatches, cleans, jerks, squats | Running |

Values are expressed as: mean (SD).
* indicates statistical significance of $p < 0.05$.
BMI: body mass index.

### Measurements

A digital scale (Super-View HW-3050, Kong Ho Instruments Co., Ltd., New Taipei City, Taiwan) was used for body mass and height measurements. The thigh and calf muscle circumferences were tape measured over the participants' muscle belly while in an upright relaxing position. A Standard Harpenden skinfold caliper (British Indicators Ltd., Luton, UK) was used for skinfold measurement. The tester pinched and pulled the tissue to ensure that muscles were not included in the measurements. Jaws of the caliper were placed over the skinfold 1 cm under the pinched fingers. The grip was released after approximately 1 second and the value on the caliper was recorded. The tester repeated the skinfold measurements three times to limit the variations (<3 mm).

A treadmill (Marquette Series 2000, Marquette Medical Systems, Inc., USA) was used in this study to define gait speeds (movement intensities), which included walking and running. To limit the effect of shoe material variations, all participants were provided the same type of shoes (wave equate 2, J1GC184801, Mizuno, Japan) during the trials. According to the preferred transition speed (average 7 km·h$^{-1}$) of the participants, a 2 km·h$^{-1}$ was added for running (9 km·h$^{-1}$), and a 2 km·h$^{-1}$ was subtracted for walking (5 km·h$^{-1}$) (Rotstein et al., 2005; Shih et al., 2016). Prior to the experiments, all the participants performed a 10-min warm-up (5-min running and 5-min static stretching), and the treadmill was inspected and calibrated. The experimental protocol is shown in Figure 1.

As the knee and ankle joints are primarily responsible for the absorption and release of energy during a gait cycle (Derrick et al., 1998), this study focused on the RF and the GMS muscles, which are the primary muscles involved in the joint functions. Accelerometers, which are sensors commonly used in quantifying soft tissue vibration characteristics during gait (Enders et al., 2014; Trama et al., 2019), were applied in

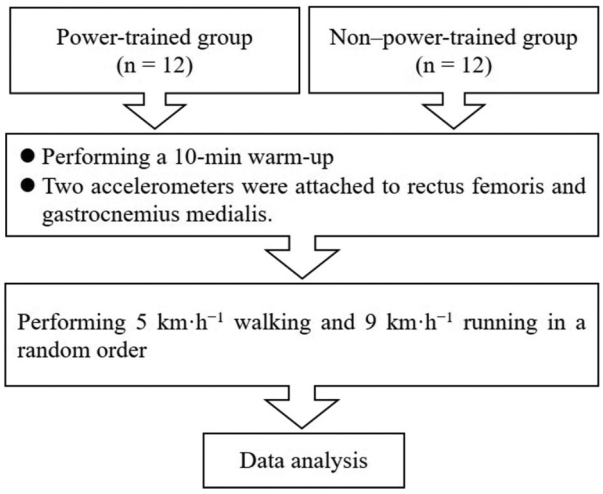


Figure 1. The experimental protocol of the study.

this study. Two triaxial accelerometers (50 G, TSD 109, Biopac System Inc., Goleta, USA; 38 mm × 28 mm × 24 mm, weight: 16 g) were attached to the soft tissue compartments of the two muscle groups, namely the RF belly (at the midpoint between the interconnection joining the anterior superior iliac spine and the patella) and GMS belly (a distance of four fingers below the tibial epicondyle) (Trama et al., 2019), by using double-sided tape and stretch adhesive bandage. The X-axis of the accelerometer was aligned to be parallel and collinear to the long axis of the shank and thigh, according to an earlier study (Trama et al., 2020). A uniaxial accelerometer was placed on the platform of the treadmill to define the gait cycle. The sampling frequency of all accelerometers was set at 1000 Hz (Khassetarash et al., 2019; Trama et al., 2020). Prior to the experiments, the accelerometer system was calibrated to ensure a force of 1 g in the direction of gravity and −1 g in the opposite direction. The accelerometers were then attached to the RF, GMS, and platform of the treadmill. The vibration frequencies of the RF and GMS soft tissue compartments at the two speeds (5 and 9 km·h$^{-1}$) were collected. The participants' arms were allowed to swing naturally during walking and running. Data of each trial were collected for 10 s when the speed and motion were in stable conditions. Measurements were obtained three times for each speed with 1-minute intervals. The participants were allowed to rest for 10 minutes between the trials. The order of experiments was counterbalanced and randomized across the participants to mitigate the occurrence of muscle fatigue.

### Data analysis

The data were acquired using LabVIEW (National Instruments Corp., Austin, USA) and processed using the Kaiser–Bessel method with an 8–50-Hz band-pass filter. A time window of 200 ms after heel strike was used for analysis (Figure 2) because the power of the acceleration signal diminished 5% below the maximum power after 200 ms for all participants (Enders et al., 2014). The frequency content of a combined 10 steps during each walking or running trial was then calculated through Fast

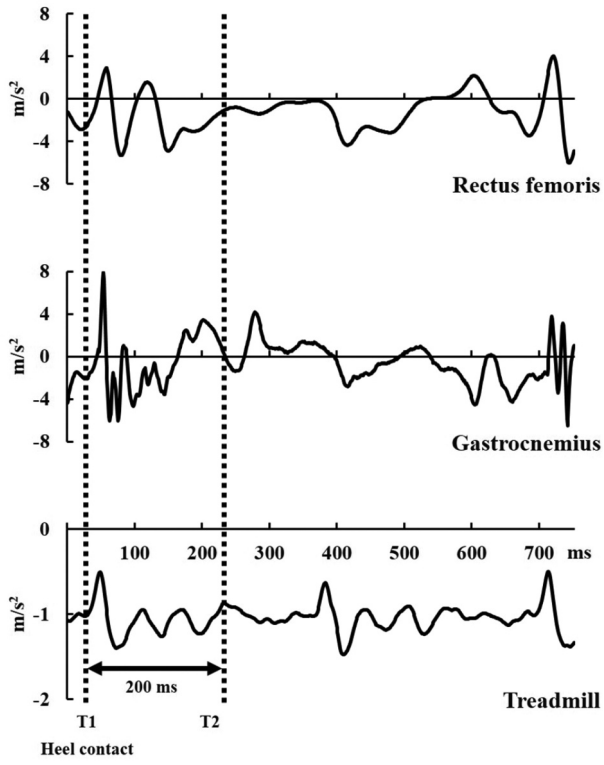


Figure 2. Exemplary raw data acquired from the accelerometers attached to the rectus femoris, gastrocnemius medialis, and the treadmill (to distinguish the instance of a heel strike). T1 is the instance of the right foot heel strike and T2 is 200 ms after heel strike.

Fourier Transform (FFT, length of 1024 samples) and presented as a power spectrum. For each power spectrum, the peak was calculated, and the calculated peaks were averaged for each condition.

### Statistical analysis

Statistical analyses were performed using SPSS (SPSS Inc., Chicago, USA). The Shapiro-Wilk and Levene analyses were applied to confirm normal distribution and that the data were homogeneously distributed. An independent t-test was used to test differences in the participants' characteristics and a two-way mixed-design analysis of variance (*ANOVA*) was used to analyse the effects of groups (power-trained and non-power-trained groups) and movement intensities (walking at 5 km·h$^{-1}$and running at 9 km·h$^{-1}$) on the RF and GMS vibration frequencies. The level of significance was defined as $\alpha = 0.05$. The eta squared ($\eta^2$) was calculated using the following formula: the sum of squares for an effect/the total sum of squares and reported as estimates of effect size (small effect: 0.01–0.06, medium effect: 0.06–0.14, and large effect: 0.14 –) (Cohen, 1992). The observed power values were also calculated.

## Results

As presented in Table 1, no significant differences in body composition parameters ($p > 0.05$) were observed between

the two groups, except for the body mass index (BMI) and the skinfold thickness of the thigh ($p < 0.05$).

Figure 3 provides the results of vibration frequency comparisons of the RF and GMS soft tissue compartments among the two athlete groups and during different movement intensities. The overall results indicated that the vibration frequencies of the RF and GMS soft tissue compartments ranged between 15 and 20 Hz in the power-trained athletes and between 9 and 13 Hz in the non-power-trained athletes. The vibration frequencies of the RF and GMS soft tissue compartments were higher during running (range: 16–20 Hz) as compared to the values during walking (range: 15–18 Hz). The statistical results showed no significant interaction between different groups (power-trained and non-power-trained) and movement intensities regarding the RF ($F_{0.95(1,22)} = 0.451$, $p = 0.510$, $\eta^2 = 0.001$, power = 0.098) and GMS ($F_{0.95(1,22)} = 0.108$, $p = 0.746$, $\eta^2 < 0.001$, power = 0.061). The main effects for the group factor in the RF ($F_{0.95(1,22)} = 63.357$, $p < 0.001$, $\eta^2 = 0.687$, power = 0.999) and GMS ($F_{0.95(1,22)} = 52.735$, $p < 0.001$, $\eta^2 = 0.652$, power = 0.999) were significantly different. Moreover, the main effects for the movement intensity factor in the RF ($F_{0.95(1,22)} = 24.912$, $p < 0.001$, $\eta^2 = 0.060$, power = 0.997) and GMS ($F_{0.95(1,22)} = 14.165$, $p = 0.001$, $\eta^2 = 0.048$, power = 0.946) were significantly different.

## Discussion

This is the first study to investigate the differences in soft tissue compartment vibration frequencies during walking and running between groups with different compositions of muscle fibre types. The major finding of this study indicates that the soft tissue compartment vibration frequencies of the quadriceps and gastrocnemius during walking and running were higher in the power-trained athletes (a difference of 6–7 Hz between power-trained and non-power-trained athletes).

It is known that vibration frequency is negatively associated with mass but positively related to stiffness (Nigg, 2010). The power-trained group, compared to the non-power-trained, had higher BMIs and larger muscle mass in their RF muscles (the same circumference with less skinfold thickness). Despite individuals with greater mass (weight) should exhibit lower soft tissue compartment vibration frequencies, the soft tissue compartment

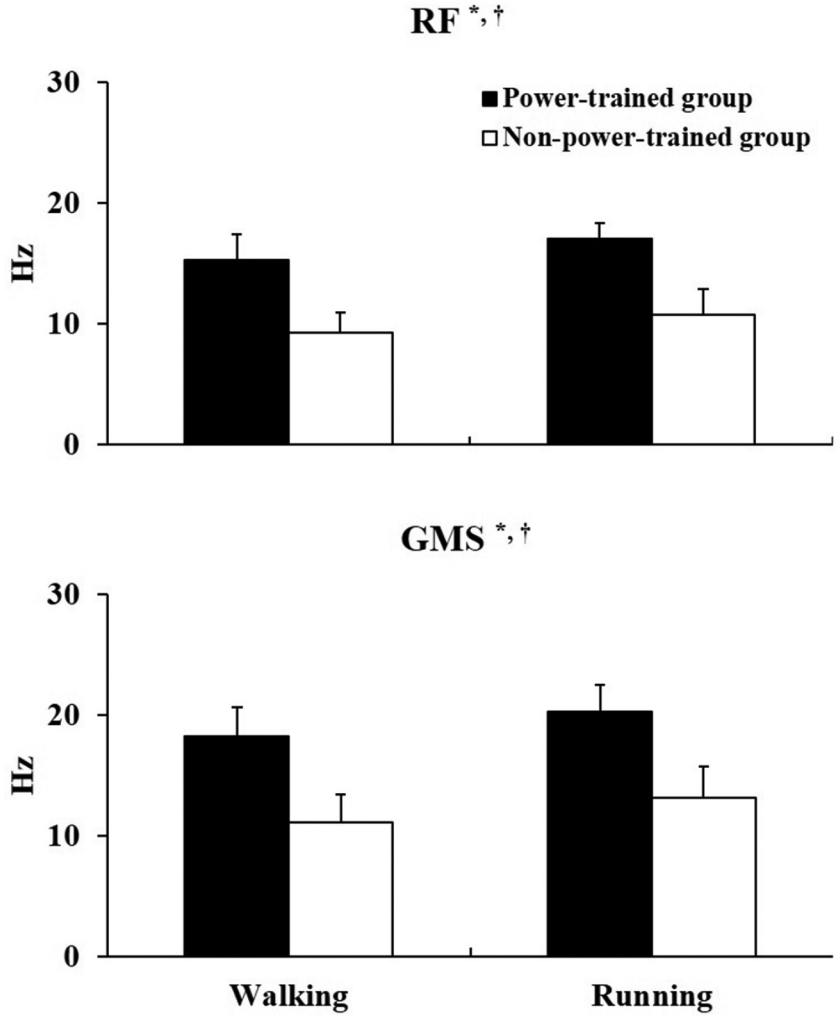


Figure 3. Comparisons of soft tissue compartment vibration frequencies between the power-trained and non-power-trained athlete groups during walking and running. RF: rectus femoris. GMS: gastrocnemius medialis. *: significant ($p < 0.05$) main effects between groups. †: significant ($p < 0.05$) main effects between walking and running.

vibration frequencies of the power-trained group were higher during walking and running. This is consistent with earlier studies in which individuals with a greater proportion of fast-twitch muscle fibres tend to generate higher soft tissue compartment vibration frequencies during isometric contractions (Mealing et al., 1996).

Negative correlations between muscle/tendon stiffness and fat layer in soft tissues were found in earlier studies (Bravo-Sanchez et al., 2019), suggesting that a thinner layer of fat will induce higher stiffness, thus leading to higher vibration frequency. This phenomenon was only observed in the RF results in our study. Even though the circumference and skinfold thickness of shank were the same in the two groups, the power-trained group had higher vibration frequencies of the GMS based on our comparisons. We speculate that this is due to the impact of recruiting a greater number of fast-twitch muscle fibres during the muscle tuning of dynamic locomotion.

Muscles are suggested to be vibration modulators that induce damping or natural frequency shifts to minimize vibration (Martinez et al., 2019; Wakeling et al., 2003). The recruitment of fast-twitch fibres has been documented as the potential cause of muscle tuning and these muscle fibres may minimize vibration through muscle activation before landing or after landing (Wakeling et al., 2001; Wakeling et al., 2002). In response to impact-related vibrations in a very short period of time at each heel strike, the extra muscle work, particularly by fast-twitch muscle fibres, may increase the vibration frequency at the heel contact.

Although the proportion of muscle fibre types was not measured in this study, the research revealed that weightlifters mostly have a considerably higher proportion of fast-twitch muscle fibres when compared to runners (Harber et al., 2002; Serrano et al., 2019). The higher proportion of fast-twitch muscle fibres of power-trained athletes is probably attributable to the fact that these athletes have been exposed to long periods of strength and power training, leading to a shift in their muscle type compositions (Wilson et al., 2012).

Based on the aforementioned findings, we speculate that in the power-trained group, a greater number of fast-twitch muscle fibres were rapidly activated in response to locomotion and muscle tuning at heel strike during gait. A result that may contribute to locomotion (such as movement propulsion and stabilization) for performance. Consequently, the vibration frequencies of the soft tissue compartments may have shifted to a higher frequency range. This can be observed in Figure 4, in which the power spectrum of the power-trained group has a greater power distribution in the high-frequency bandwidth of 22–35 Hz. We can reasonably infer that in the power-trained group, more fast-twitch fibres were activated for increased damping or neutral frequency shift, although the amount of extra muscle work required for muscle tuning is still unknown in this study.

In particular, the interesting phenomenon observed in this study is often overlooked during the training and competition of power-trained athletes. Fast-twitch fibres are more fatigable during excessively repeated activation and the fatigue will reduce the capability to induce muscle tuning, leading to an increased risk of impact-related injury (Friesenbichler et al., 2011; Khassetarash et al., 2015). Earlier studies have indicated

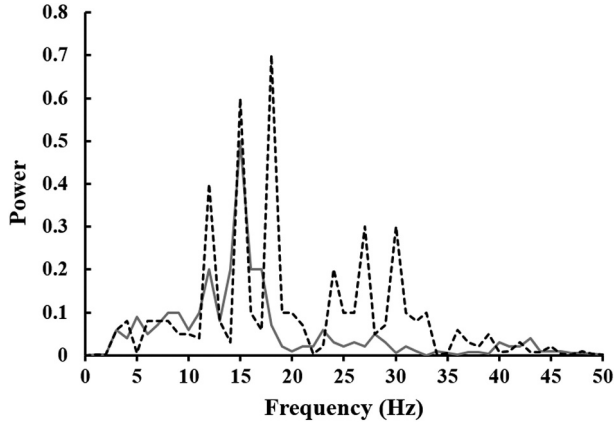


Figure 4. A power spectrum generated from signals acquired from accelerometers mounted on the gastrocnemius muscles of non–power-trained (solid line) and power-trained (dashed line) groups during running at 9 km·h$^{-1}$.

that compression garments can dampen vibration during continuous impact exercise activities for protection against muscle-related injury and fatigue (Doan et al., 2003; Kraemer et al., 1998). Therefore, the current study suggests that power-trained athletes who possess a larger proportion of fast-twitch fibres can consider using compression sportswear to inhibit excessive oscillation during prolonged high-impact exercise activities (jogging, running, and jumping).

In this study, the muscle vibration frequency increased with the gait speeds and movement intensities, a finding that is consistent with that of Boyer and Nigg (2004), who used an accelerometer to measure the influence of muscle vibration on the RF, hamstrings, tibialis anterior, and gastrocnemius at different running speeds. They found that an increase in running speed was accompanied by an increase in the vibration frequencies of soft tissue compartments. They also indicated that this increase was in response to the input vibration frequency, which was closer to the natural frequency of the soft tissue compartments. We can then speculate that during an increase of intensity in dynamic exercises, more motor units will be recruited in response to the demands of increased locomotion, generating higher vibration frequencies of the soft tissue compartments.

Previous studies have indicated that certain shoes with varying mechanical properties can reduce unnecessary muscle tuning by ensuring that the input frequency is separated from the natural frequency of soft tissue compartments (Nigg, 2010; Wakeling, Pascual et al., 2002). This process may save additional muscle work, improve performance, and even delay the onset of fatigue (Nigg, 2010; Wakeling et al., 2002). A feasible approach is to utilize wearable accelerometers by monitoring and quantifying vibration frequencies of soft tissue compartments during dynamic movements to reflect the status of muscle tuning and to improve performance and damping effects. This can be developed as a non-invasive approach for novel designs of wearable devices that can estimate the change of muscle fibre type composition before and after training.

This is an initial study that was designed to understand if individuals with different compositions of muscle fibre types

would result in distinct effects on soft tissue compartment vibration frequencies during dynamic movement. Therefore, we would like to report the limitations of this study to improve future experimental designs. First, this study did not histologically analyse the composition of muscle fibres. Second, the electromyography was not concurrently acquired during the trials. Nonetheless, we hope that the obtained findings and results of this study can benefit the development of similar designs.

## Conclusions

Different muscle fibre compositions and movement intensities can potentially alternate soft tissue compartment vibration frequencies of quadriceps and gastrocnemius muscles. In particular, the power-trained athletes exhibited higher soft tissue compartment vibration frequencies during running, indicating that fast-twitch fibres might have been activated to accommodate the demands of locomotion and muscle tuning. Since early dysfunction of muscle tuning during prolonged running might occur in these athletes, further investigations will be necessary to improve overall training outcomes.

## Disclosure statement

No potential conflict of interest was reported by the authors.

## Funding

This work was supported by the [Ministry of Science and Technology] under Grant [number NSC 97-2622-B-154-001-CC2] and the [Ministry of Education of Taiwan] under Grant [Higher Education Sprout Project of National Taiwan Normal University].

## ORCID

Wen-Wen Yang http://orcid.org/0000-0002-3977-9221
Vincent Chiun-Fan Chen http://orcid.org/0000-0001-6688-8258
Tzyy-Yuang Shiang http://orcid.org/0000-0002-1641-3091

## References

Boyer, K. A., & Nigg, B. M. (2004). Muscle activity in the leg is tuned in response to impact force characteristics. *Journal of Biomechanics*, *37*(10), 1583–1588. https://doi.org/doi:10.1016/j.jbiomech.2004.01.002

Bravo-Sanchez, A., Abian, P., Jimenez, F., & Abian-Vicen, J. (2019). Myotendinous asymmetries derived from the prolonged practice of badminton in professional players. *PloS One*, *14*(9), e0222190. https://doi.org/doi:10.1371/journal.pone.0222190

Cohen, J. (1992). A power primer. *Psychological Bulletin 112*(1), 155–159. https://doi.org/doi:10.1037/0033-2909.112.1.155

Derrick, T. R., Hamill, J., & Caldwell, G. E. (1998). Energy absorption of impacts during running at various stride lengths. *Medicine and Science in Sports and Exercise*, *30*(1), 128–135. https://doi.org/doi:10.1097/00005768-199801000-00018

Doan, B. K., Kwon, Y. H., Newton, R. U., Shim, J., Popper, E. M., Rogers, R. A., … Kraemer, W. J. (2003). Evaluation of a lower-body compression garment. *Journal of Sports Sciences*, *21*(8), 601–610. https://doi.org/doi:10.1080/0264041031000101971

Enders, H., von Tscharner, V., & Nigg, B. M. (2014). The effects of preferred and non-preferred running strike patterns on tissue vibration properties. *Journal of Science and Medicine in Sport*, *17*(2), 218–222. https://doi.org/doi:10.1016/j.jsams.2013.03.015

Friesenbichler, B., Stirling, L. M., Federolf, P., & Nigg, B. M. (2011). Tissue vibration in prolonged running. *Journal of Biomechanics*, *44*(1), 116–120. https://doi.org/doi:10.1016/j.jbiomech.2010.08.034

Fry, A. C., Schilling, B. K., Staron, R. S., Hagerman, F. C., Hikida, R. S., & Thrush, J. T. (2003). Muscle fiber characteristics and performance correlates of male Olympic-style weightlifters. *Journal of Strength and Conditioning Research*, *17*(4), 746–754. https://doi.org/doi:10.1519/1533-4287(2003)017<0746:mfcapc>2.0.CO;2

Harber, M. P., Gallagher, P. M., Trautmann, J., & Trappe, S. W. (2002). Myosin heavy chain composition of single muscle fibers in male distance runners. *International Journal of Sports Medicine*, *23*(7), 484–488. https://doi.org/doi:10.1055/s-2002-35067

Hodson-Tole, E. F., & Wakeling, J. M. (2009). Motor unit recruitment for dynamic tasks: Current understanding and future directions. *Journal of Comparative Physiology B*, *179*(1), 57–66. https://doi.org/doi:10.1007/s00360-008-0289-1

Islam, A., Sundaraj, K., Ahmad, B., Ahamed, N. U., & Ali, A. (2012). Mechanomyography sensors for muscle assessment: A brief review. *Journal of Physical Therapy Science*, *24*(12), 1359–1365. https://doi.org/doi:10.1589/jpts.24.1359

Khassetarash, A., Hassannejad, R., Enders, H., & Ettefagh, M. M. (2015). Damping and energy dissipation in soft tissue vibrations during running. *Journal of Biomechanics*, *48*(2), 204–209. https://doi.org/doi:10.1016/j.jbiomech.2014.11.051

Khassetarash, A., Hassannejad, R., Ettefagh, M. M., & Oskouei, A. E. (2019). Vibration settling time of the gastrocnemius remains constant during an exhaustive run in rear foot strike runners. *Journal of Biomechanics*, *93*, 140–146. https://doi.org/doi:10.1016/j.jbiomech.2019.06.026

Khassetarash, A., Hassannejad, R., Ettefagh, M. M., & Sari-Sarraf, V. (2015). Fatigue and soft tissue vibration during prolonged running. *Human Movement Science*, *44*, 157–167. https://doi.org/doi:10.1016/j.humov.2015.08.024

Kraemer, W. J., Bush, J. A., Newton, R. U., Duncan, N. D., Volek, J. S., Denegar, C. R., … Sebastianelli, W. J. (1998). Influence of a compression garment on repetitive power output production before and after different types of muscle fatigue. *Sports Medicine Training and Rehabilitation*, *8*(2), 163–184. https://doi.org/doi:10.1080/15438629809512525

Lee, S. S., de Boef Miara, M., Arnold, A. S., Biewener, A. A., & Wakeling, J. M. (2013). Recruitment of faster motor units is associated with greater rates of fascicle strain and rapid changes in muscle force during locomotion. *Journal of Experimental Biology*, *216*(2), 198–207. https://doi.org/doi:10.1242/jeb.072637

Loeb, G. E. (1985). Motoneurone task groups: Coping with kinematic heterogeneity. *Journal of Experimental Biology*, *115*, 137–146. https://jeb.biologists.org/content/115/1/137.long

Martinez, A., Lam, C. K., von Tscharner, V., & Nigg, B. M. (2019). Soft tissue vibration dynamics after an unexpected impact. *Physiological Reports*, *7*(2), e13990. https://doi.org/doi:10.14814/phy2.13990

Mealing, D., Long, G., & McCarthy, P. W. (1996). Vibromyographic recording from human muscles with known fibre composition differences. *British Journal of Sports Medicine*, *30*(1), 27–31. http://dx.doi.org/10.1136/bjsm.30.1.27

Nigg, B. M. (2010). *Biomechanics of sports shoes*. Topline Printing Inc.

Nigg, B. M., & Liu, W. (1999). The effect of muscle stiffness and damping on simulated impact force peaks during running. *Journal of Biomechanics*, *32*(8), 849–856. https://doi.org/doi:10.1016/S0021-9290(99)00048-2

Rotstein, A., Inbar, O., Berginsky, T., & Meckel, Y. (2005). Preferred transition speed between walking and running: Effects of training status. *Medicine and Science in Sports and Exercise*, *37*(11), 1864–1870. https://doi.org/doi:10.1249/01.mss.0000177217.12977.2f

Serrano, N., Colenso-Semple, L. M., Lazauskus, K. K., Siu, J. W., Bagley, J. R., Lockie, R. G., … Galpin, A. J. (2019). Extraordinary fast-twitch fiber abundance in elite weightlifters. *PloS One*, *14*(3), e0207975. https://doi.org/doi:10.1371/journal.pone.0207975

Shih, Y., Chen, Y. C., Lee, Y. S., Chan, M. S., & Shiang, T. Y. (2016). Walking beyond preferred transition speed increases muscle activations with a shift from inverted pendulum to spring mass model in lower

extremity. *Gait and Posture*, *46*, 5–10. https://doi.org/doi:10.1016/j.gaitpost.2016.01.003

Trama, R., Blache, Y., & Hautier, C. (2019). Effect of rocker shoes and running speed on lower limb mechanics and soft tissue vibrations. *Journal of Biomechanics*, *82*, 171–177. https://doi.org/doi:10.1016/j.jbiomech.2018.10.023

Trama, R., Hautier, C., & Blache, Y. (2020). Input and soft-tissue vibration characteristics during sport-specific tasks. *Medicine and Science in Sports and Exercise*, *52*(1), 112–119. https://doi.org/doi:10.1249/MSS.0000000000002106

Von Tscharner, V., & Goepfert, B. (2006). Estimation of the interplay between groups of fast and slow muscle fibers of the tibialis anterior and gastrocnemius muscle while running. *Journal of Electromyography and Kinesiology*, *16*(2), 188–197. https://doi.org/doi:10.1016/j.jelekin.2005.07.004

Wakeling, J. M., Liphardt, A. M., & Nigg, B. M. (2003). Muscle activity reduces soft-tissue resonance at heel-strike during walking. *Journal of Biomechanics*, *36*(12), 1761–1769. https://doi.org/doi:10.1016/S0021-9290(03)00216-1

Wakeling, J. M., & Nigg, B. M. (2001). Modification of soft tissue vibrations in the leg by muscular activity. *Journal of Applied Physiology*, *90*(2), 412–420. https://doi.org/doi:10.1152/jappl.2001.90.2.412

Wakeling, J. M., Nigg, B. M., & Rozitis, A. I. (2002). Muscle activity damps the soft tissue resonance that occurs in response to pulsed and continuous vibrations. *Journal of Applied Physiology*, *93*(3), 1093–1103. https://doi.org/doi:10.1152/japplphysiol.00142.2002

Wakeling, J. M., Pascual, S. A., & Nigg, B. M. (2002). Altering muscle activity in the lower extremities by running with different shoes. *Medicine and Science in Sports and Exercise*, *34*(9), 1529–1532. https://doi.org/doi:10.1249/01.MSS.0000027714.70099.08

Wakeling, J. M., & Rozitis, A. I. (2004). Spectral properties of myoelectric signals from different motor units in the leg extensor muscles. *Journal of Experimental Biology*, *207*(Pt 14), 2519–2528. https://doi.org/doi:10.1242/jeb.01042

Wakeling, J. M., Uehli, K., & Rozitis, A. I. (2006). Muscle fibre recruitment can respond to the mechanics of the muscle contraction. *Journal of the Royal Society Interface*, *3*(9), 533–544. https://doi.org/doi:10.1098/rsif.2006.0113

Wakeling, J. M., Von Tscharner, V., Nigg, B. M., & Stergiou, P. (2001). Muscle activity in the leg is tuned in response to ground reaction forces. *Journal of Applied Physiology*, *91*(3), 1307–1317. https://doi.org/doi:10.1152/jappl.2001.91.3.1307

Wilson, J. M., Loenneke, J. P., Jo, E., Wilson, G. J., Zourdos, M. C., & Kim, J. S. (2012). The effects of endurance, strength, and power training on muscle fiber type shifting. *Journal of Strength and Conditioning Research*, *26*(6), 1724–1729. https://doi.org/doi:10.1519/JSC.0b013e318234eb6f