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Research article

Reliability of Soft Tissue Vibration Measurement and Number of Steps Demanded during Treadmill Running

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Abstract

The present study aims to determine the test-retest reliability of the input signal (INPUT) of foot impact and soft tissue vibration (STV) of the lower limb muscles during treadmill running. Twenty-six recreational runners participated in three running trials at constant velocity (10 km/h) within two days. The INPUT and STV of gastrocnemius medialis (GAS) and vastus lateralis (VL) were extracted from 100 steps measured by three triaxial accelerometers. The Intraclass Correlation Coefficient (ICC) was calculated to determine the Intra-trial and Inter-day reliability of the different variables. Intra-trial reliability results indicated that most of the INPUT and GAS STV parameters, except for damping coefficient and setting time, have good to excellent reliability ($0.75 < ICC < 0.9$) from the beginning of the run (10 steps) to the end. In contrast, only 4 VL STV parameters showed good reliability. Furthermore, inter-trial reliability measured on day one showed that the number of reliable parameters reduced, especially for VL STV, and more steps were required ($20 < steps < 80$) to achieve good reliability. Inter-day reliability results showed that only one VL STV parameter reached good reliability. Therefore, the present results show that the measurement of the foot impact and the calf muscle vibrations present a good to excellent reliability measured on a single trial and two trials carried out on the same day. The reliability of these parameters remains good when comparing two days of experimentation. We recommend measuring impact and STV parameters during treadmill running in the same session.

Key words: Soft tissue, vibration, reliability, treadmill running.

Introduction

Running is one of the most popular sports activities that has become increasingly popular in the last two decades (Hulteen et al., 2017). There is a high rate of running-related musculoskeletal injuries, especially to the lower extremities (Hollander et al., 2021). The incidence of lower extremity running injuries ranged from 19.4% to 79.3% (van Gent et al., 2007), where the highest proportion of injury prevalence are the ankle, knee, and lower leg (Kakouris et al., 2021). Additionally, one of the recognized sources of running injuries was related to external impact as the initial input (INPUT) into the musculoskeletal system during the stance phase (i.e., vertical ground reaction force), which could potentially induce the musculoskeletal injuries (Johnson et al., 2021; Khassetarash et al., 2015). Previous evidence demonstrates that ground impacts generate the shock wave to induce soft tissue vibrations (STV) that may negatively affect the lower extremity muscles, including fatigue, pain and loss of function, even if the vibration is very short (Cronin et al., 2004). According to the vibration theory, if the vibration frequency is close to the natural frequency of the soft tissue, resonant vibrations could be amplified, increasing the potential muscle injury risk (Boyer and Nigg, 2006; Enders et al., 2012; Friesenbichler et al., 2011; Wakeling and Nigg, 2001a). Consequently, it is crucial to characterize the STV parameters (amplitude, frequency, damping) to better understand the lower extremity injury mechanism during running.

Meanwhile, most previous studies have developed methods to detect and quantify (Boyer and Nigg, 2006; Boyer and Nigg, 2007; Wakeling and Nigg, 2001a) and model (Enders et al., 2012; Khassetarash et al., 2015) the soft tissue vibration. However, optimized and reliable input data are necessary to support the tested hypotheses, leading to robust results. Concerns about reproducibility in human movement biomechanics multiply in the scientific community. Low reproducibility leads to low statistical power, poor replicability of the studies, and bloated effect sizes (Knudson, 2017). Although running is a continuous activity that presents less variability compared to the nonconsecutive movement (e.g., a discrete movement such as a jump and landing), running also requires the necessary number of steps to achieve performance stability. Recent literature reported that running biomechanics required at least 25 participants and analyzing 25 steps to obtain an optimized kinetics data stability (e.g., ground reaction force) with a satisfying statistical power (Oliveira and Pirscoveanu, 2021). Unfortunately, to our best acknowledge, no investigation was conducted on STV reliability has been published about the reliability of the STV measurement in the running. Additionally, studies have yet to report the required number of steps to achieve good reliability with the variability of STV variables.

Therefore, this study aimed to *i*) assess the repeatability and reproducibility, thus the intra-trial, intra-, and inter-day reliability of the STV for a given treadmill running velocity, and *ii*) determine a minimum number of steps required to reach data stability to obtain a reliable evaluation of soft tissue vibration.

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Methods

Participants

Twenty-six recreational runners (21 males and 5 females, age: 28.1 ± 5.2 years, height: 173.9 ± 5.7 cm, weight: 69.2 ± 7.9 kg, BMI: 22.8 ± 2.42 kg.m^{-2}), training volume: 3.5 ± 0.7 h. week^{-1}, experience training: 5.2 ± 5.9 years, velocity maximal aerobic [VMA]: 15.2 ± 1.4 km/h) volunteered to participate in the present study. The prior sample size (n = 26) was calculated by test-retest reliability design, which assumes an expected ICC = 0.85 with a precision value of 0.1 (± expected ICC), and the drop rate is expected of 10% (Arifin, 2018). All the participants had not suffered any lower extremities injuries during the past six months. Leading up to the experiment, participants followed their regular physical activity but avoided strenuous loading at least 48 hours before testing. According to the Declaration of Helsinki, all the participants signed informed-consent documentation approved by the local ethics committee Lyon II.

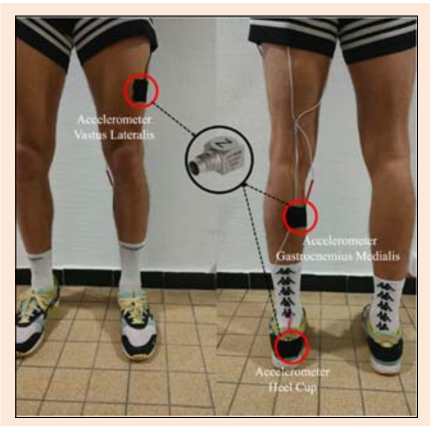

Figure 1. Locations of the 3 accelerometers on the lower limb.

Experimental procedure

A within-subject test-retest measures study design was used to determine the intra- and inter-test reliability of vibration parameters/variables measured from running. The protocol consisted of two experimental testing sessions within two days. For each session, all the participants performed firstly a standard warm-up (i.e., 10-minute treadmill running with the preferred velocity) and a familiarization session including 7 minutes running on the treadmill at the required velocity (i.e., 10 km/h). This standard submaximal running velocity was fixed based on the participants' self-selected velocity was between 2.56 to 2.89 m/s, corresponding to their approximately 70% VMA (i.e., ~ 15km/h). It permits the participant to adapt the treadmill running to control for the influence of velocity and potential fatigue on the foot impact input. After that, three accelerometers were equipped for the participants (Figure 1). For the first test day (D_1), the participants realized two trials of running ($D_{1\text{-}A}$ and $D_{1\text{-}B}$) at a constant velocity of 10 km/h, separated by a 10-minutes recovery period. The accelerometers were unequipped and re-equipped between two trials and two days with the same sensor location, measured before the test of $D_{1\text{-}A}$. For the one subsequent day (D_2), all the participants performed a second running test at the same running velocity 1 to 2 days after the first test. All testing sessions were performed in the same condition (e.g., exact location, same ambient temperature, same time of the day).

Instrumentation and data collection

The input signal (INPUT) of foot impact and STV of the lower limb were measured using three triaxial accelerometers (Dytran Instrument Inc., Chatsworth, California, USA, acceleration amplitude: ± 1000 m·s^{-2}, 2000 Hz), which were taped and secured with cohesive tape to the shoe's heel cup, muscle belly of the gastrocnemius medialis (GAS), and vastus lateralis (VL) of the dominant leg (i.e., kicking leg) (Trama et al., 2020). The accelerometer of INPUT was attached to the shoe's heel cup with the y-axis oriented vertically to determine the moment of impact. In addition, the y-axis was aligned parallel to the shank and the thigh longitudinal axis. The z-axis was positioned normally to the skin surface and the x-axis normal to the z-y plane for GAS and VL, respectively. The points of interest and the precise sensor location of the accelerometers were recorded to reduce data measurement errors during the protocols. At least 150 impacts were recorded for each running trial within ~ 3 minutes. The software EMGworks (Delsys®, Natick, MA) was used to record and synchronize the three accelerometers' signals.

Data analysis

The raw acceleration data for INPUT and OUTPUT acceleration signals were filtered firstly using a 2nd order band-pass Butterworth filter at 10-120 Hz to remove the movement artifacts and electronic noise. The impacts were detected by INPUT filtered data when the time derivate of the norm of the acceleration signal (i.e., the jerk) reached 5000 m·s^{-3} aimed to determine the INPUT signal and OUTPUT signal. The norm of the signal was calculated based on filtered data of the three-axis of acceleration using the square root method. To avoid edge effects, the signal analysis was performed on a 650-ms window length around the impact (i.e., 200 ms before and 450 ms after the impact). All data analyses were directly detected and analyzed with customized scripts in Matlab (R2020b, The Mathworks, Natick, USA).

Temporal-domain analysis

The peak acceleration (Acc_{Peak}) and the integrated acceleration (iAcc) were respectively calculated as the maximum of the absolute amplitude of the filtered signal and the area under the curve of the filtered signal of the INPUT and OUTPUT.

Frequency-domain analysis

A Fast Fourier Transformation (FFT) was used to perform frequency-domain analysis to estimate the amplitude spectrum normalized by the frequency resolution. The median frequency (MDF) was the frequency that split the amplitude or power spectrum in half. The mean frequency (MNF) was calculated as the average value of the spectrum curve. The peak energy ($Energy_{peak}$) and total energy ($Energy_{total}$) were calculated as the maximum amplitude of the spectrum and the area under the spectrum curve both for INPUT and OUTPUT acceleration signal (Duhamel and Vetterli, 1990).

Temporal-frequency domain analysis

A continuous wavelet transform (CWT), using a filter bank of 39 Morse wavelets (Trama et al., 2020), was used to calculate all the variables mentioned above in the Frequency-domain analysis. The main frequency (MF) corresponds to the mean of the median frequencies measured at each sample time. In addition, the damping coefficient (Damp) was calculated using the decrement of logarithm power, estimated by the least-squares minimization (Enders et al., 2012; Trama et al., 2019; 2020). The settling time (ST) was defined as the time between the maximum amplitude and 10% of the amplitude of the spectrum curve (Khassetarash et al., 2019).

Statistical analysis

Intra-trial, intra- and inter-day reliability indicators were calculated to determine the variables' stability using the test-retest Intraclass Correlation Coefficient (ICC) among D_{1-A}, D_{1-B}, and D_2 through a two-way mixed-effects model ICC (3, k) based on the mean of multiple measurement (Watson and Petrie, 2010; Weir, 2005). The ICC was iteratively calculated as incremental every 10 steps for the combination of steps ranging from 10 to 100 steps. The thresholds used to interpret using criteria: poor (ICC < 0.5), moderate (0.5 ≤ ICC < 0.75), good (0.75 ≤ ICC < 0.9), excellent (ICC ≥ 0.90) (Koo and Li, 2016). In addition, the Coefficient of Variation (CV) was also calculated for each variable of the entire 100 steps expressed as a %. The criterion alpha level for establishing statistical significance was set to 0.05. Descriptive statistics are presented as mean ± SD with 95% CI. All the statistical procedures were completed using a customized script on Matlab (R2021b, The Mathworks, Natick, USA).

Results

Intra-trial reliability

The intra-trial reliability of D_{1-A} indicated that all the variables of the INPUT signal during the first trial except Acc_{peak}, MF_{CWT}, Damp, and ST had good to excellent overall reliability (Table 1, 0.80 < ICC < 0.93, 8.39 < CV < 66.48) across 100-steps (Figure 2-A). However, the MDF_{FFT} of the INPUT signal had good reliability from the beginning and then drifted to moderate reliability after 90 steps (i.e., less than 0.75). Likewise, all variables of the GAS signal also demonstrated good overall reliability (Table 1, Figure 2-D, 0.80 < ICC < 0.91, 10.07 < CV < 70.68) except variable MF_{CWT}, Damp, and ST (ICC < 0.75) across all steps interval. In contrast, MDF_{FFT}, MDF_{CWT}, MNF_{FFT}, and MNF_{CWT} of VL STV showed good reliability (Table 1, Figure 2-G, 0.77 < ICC < 0.84, 12.80 < CV < 58.69). Additionally, the MDF_{FFT} of the VL STV had good reliability at 30 steps, and then reliability declined to a moderate level after 40 steps (i.e., less than 0.75).

Intra-day reliability

The intra-day reliability between D_{1-A} and D_{1-B} revealed that all the variables of INPUT had good to excellent overall reliability excepting MF_{CWT}, $Energy_{Total}$ irrespectively of the calculation method, and ST (Table 2, Figure 1-B, 0.76 < ICC < 0.92, 9.96 < CV < 66.64). Furthermore, the MDF_{FFT}, MDF_{CWT}, MNF_{FFT} and, MNF_{CWT} had the good to excellent reliability across all the steps interval (Table 2, Figure 2-B, 0.78 < ICC < 0.91, 9.96 < CV < 16.19). At the same time, the Acc_{Peak}, iAcc, MF_{CWT}, and $Energy_{Peak\_FFT}$, whatever the calculation method, indicated a tendency of rising reliability following the step increased which reached good reliability after 80, 70, 70, 50, 90, and 70, respectively. Similarly, all the variables of GAS STV had moderate to good reliability excepting MF_{CWT}, and ST (Figure 2-E, 0.72 < ICC < 0.86, 11.75 < CV < 48.75), while MDF_{CWT}, MNF_{FFT}, MNF_{CWT}, $Energy_{Peak\_FFT}$ had always good reliability at the beginning of the running until the end (Table 2, 0.75 < ICC < 0.85, 11.75 < CV < 20.66). In addition, there is a tendency of rising reliability following the step increase for the variables Acc_{Peak}, iAcc, MDF_{FFT}, $Energy_{Peak\_CWT}$, $Energy_{Peak\_FFT}$, $Energy_{Total\_CWT}$, and Damping, which reached good reliability after 20, 20, 90, 40, 10, 20, and 20 steps, respectively. In contrast, only MF_{CWT} of VL STV showed good reliability (Figure 2-H, ICC = 0.84, CV = 34.85) after 20-steps and 60-steps, respectively.

Inter-day reliability

The inter-day reliability of the INPUT signal between D_{1-A} and D_2 indicated that $Energy_{Peak}$, whatever the calculation method, had good overall reliability from the beginning of the running until 100-steps (Table 3, Figure 2-C, 0.81 < ICC < 0.90, 25.1 < CV < 30.03). Moreover, the Acc_{Peak}, iAcc, MF_{CWT}, $Energy_{Total\_FFT}$, and $Energy_{Total\_CWT}$ reached a good reliability after 60, 20, 90, 60, 60 steps, respectively (Figure 2-C, 0.77 < ICC < 0.83, 13.07 < CV < 30.03). However, the MDF_{FFT} of the INPUT signal had good reliability (ICC = 0.75) only at 60 steps. In addition, Acc_{Peak} of GAS STV has good ICC from the beginning of the run until the end, while MDF_{FFT}, MF_{CWT}, $Energy_{Total\_FFT}$ of GAS reached good reliability after 20, 40, 20-steps, respectively reliability (Figure 2-F, 0.75 < ICC < 0.85, 23.5 < CV < 66.86). Despite the iAcc of the GAS signal reached to good reliability across different steps interval (i.e., 50, 60, 70), it also shifts to moderate reliability after 80 steps (Figure 2-F, ICC < 0.75). Similarly, the MF_{CWT} of the VL signal reached good reliability only at 70 steps (Figure 2-I, ICC = 0.75) and then shifted to moderate reliability until 100 steps.

Discussion

To the best of our knowledge, this is the first study to evaluate the intra-trial, intra-, and inter-day reliability of vibration parameters during treadmill running. The findings demonstrated that most of the INPUT signal and GAS STV parameters, except for damping coefficient and setting time, reached excellent intra-trial and intra-day reliability from the first 10 steps. The reliability of all the parameters decreased significantly from intra- trial to intra- and inter-day comparison, indicating that artificial factors such as reequipping subjects in an identical manner remain challenging.

Comparing the CV of all the parameters obtained with FFT and CWT tended to demonstrate very few differences. However, it is essential to note that the ICC calculated for a given parameter is comparable between the two methods. Intra- trial analysis of D_{1-A} demonstrated good to excellent reliability for 9 INPUT variables, 10 GAS STV variables, and 4 VL STV variables (Table 1). All other calculated variables presented at least moderate reliability (ICC ≈ 0.5) except VL STV settling time. The INPUT and STV were reliably measured, given that the protocol does not require to unequip and reequip devices in a unique trial without changing the sensor's location. This finding gives complementary information to analyze the effects of different running shoes or equipment like compression garments on STV and the alterations in STV induced by fatigue and muscle soreness during a single trial. Interestingly, although the INPUT signal variable always indicated excellent reliability, the evolution of the reliability shows the tendency to be relatively reduced after 20 steps. It could be related to the fact that the subjects might change their running pattern to adopt a more shuffling gait when accustomed to this situation. Furthermore, the number of excellent ICC is lower for the VL STV compared to INPUT signal and GAS STV, which can be explained by the influence of the number of degrees of freedom that increases between the calf and the thigh, and the relative impact of the other body segments results in augmenting the magnitude of the STV variability. Interestingly damping coefficient and settling time were the less reliable parameters compared to others variables, whatever the measurement location (i.e., INPUT, GAS, and VL). This may be partly explained by the calculation method, which depends more on the amplitude and time of the spectrum-time curve (Wakeling and Nigg, 2001a).

The intra-day reliability of D1 demonstrated that more than 75% of the INPUT and GAS STV variables presented good reliability (0.75 < ICC < 0.92, Table 2). Even though most of the other calculated parameters (2 for the INPUT, 1 for the GAS STV, and 8 for the VL STV) presented moderate reliability, it is important to observe that 6 STV variables showed poor reliability, especially for the peak acceleration, total energy STV irrespectively of the calculation method, and damping coefficient of VL STV (Table 2). The decrease in the reliability of the measurements between the two trials is related to de-equipping and reequipping the participant-induced confounding factors.

Table 1. Intra-trial reliability of day one for heel impact signal and soft tissue vibration parameters.

	Variable	Method	Mean ± SD	ICCmax 95%CI	ICCmean 95%CI	CV 95%CI	N Step
INPUT	AccPeak ($m \cdot s^{-2}$)		184.01 ± 46.87	0.72[0.59;0.84]	0.7[0.58;0.83]	25.47[23.8;27.15]	/
	iAcc (UA. s)		4.66 ± 1.23	0.93[0.88;0.96]	0.88[0.81;0.93]	26.3[24.63;27.98]	10
	MDF (Hz)	FFT	66.5 ± 11.78	0.8[0.63;0.87]	0.74[0.63;0.86]	17.72[16.04;19.4]	10
		CWT	78.68 ± 11.72	0.85[0.73;0.91]	0.82[0.73;0.9]	14.89[13.22;16.57]	10
	MNF (Hz)	FFT	73.17 ± 8.95	0.86[0.76;0.92]	0.82[0.73;0.9]	12.24[10.56;13.91]	10
		CWT	83.03 ± 8.36	0.88[0.78;0.93]	0.85[0.76;0.92]	10.07[8.39;11.74]	10
	MF (Hz)	CWT	37.79 ± 25.5	0.51[0.38;0.68]	0.46[0.34;0.64]	67.49[65.81;69.16]	/
	EnergyPeak (UA)	FFT	3.42 ± 1.02	0.91[0.85;0.95]	0.85[0.77;0.92]	29.79[28.11;31.46]	10
		CWT	2.63 ± 0.93	0.91[0.85;0.95]	0.85[0.77;0.92]	35.33[33.66;37.01]	10
	EnergyTotal (UA·s)	FFT	274.31 ± 82.65	0.88[0.81;0.94]	0.84[0.75;0.91]	30.13[28.45;31.8]	10
		CWT	276.88 ± 79.68	0.89[0.82;0.94]	0.84[0.76;0.92]	28.77[27.1;30.45]	10
	Damp ($m \cdot s^{-2} \cdot s^{-1}$)	CWT	44.84 ± 12.02	0.64[0.5;0.79]	0.51[0.37;0.68]	26.8[25.12;28.47]	/
	ST (s)	CWT	0.07 ± 0.01	0.59[0.43;0.75]	0.39[0.27;0.57]	21.15[19.48;22.83]	/
GAS	AccPeak ($m \cdot s^{-2}$)		73.92 ± 29.51	0.85[0.76;0.92]	0.78[0.68;0.88]	39.91[38.24;41.59]	10
	iAcc (UA. s)		4.19 ± 0.88	0.8[0.69;0.89]	0.8[0.69;0.89]	20.94[19.26;22.62]	10
	MDF (Hz)	FFT	29.69 ± 4.87	0.84[0.71;0.9]	0.82[0.73;0.9]	16.4[14.73;18.08]	10
		CWT	39.86 ± 6.1	0.81[0.67;0.88]	0.81[0.71;0.9]	15.31[13.64;16.99]	10
	MNF (Hz)	FFT	40.72 ± 5.21	0.84[0.7;0.9]	0.83[0.74;0.91]	12.8[11.13;14.48]	10
		CWT	51.39 ± 7.25	0.89[0.75;0.92]	0.88[0.82;0.94]	14.11[12.43;15.79]	10
	MF (Hz)	CWT	16.94 ± 6.67	0.67[0.53;0.82]	0.59[0.45;0.74]	39.39[37.72;41.07]	/
	EnergyPeak (UA)	FFT	4.08 ± 1.18	0.86[0.78;0.93]	0.83[0.74;0.91]	28.81[27.14;30.49]	10
		CWT	3.06 ± 0.77	0.81[0.7;0.9]	0.78[0.68;0.88]	25.02[23.35;26.7]	10
	EnergyTotal (UA·s)	FFT	132.65 ± 38.46	0.83[0.73;0.91]	0.79[0.68;0.88]	28.99[27.31;30.67]	10
		CWT	142.74 ± 39.05	0.81[0.7;0.9]	0.76[0.65;0.87]	27.36[25.68;29.03]	10
	Damp ($m \cdot s^{-2} \cdot s^{-1}$)	CWT	17.77 ± 8.34	0.6[0.47;0.76]	0.56[0.43;0.73]	46.95[45.27;48.63]	/
	ST (s)	CWT	0.14 ± 0.03	0.53[0.39;0.71]	0.49[0.36;0.67]	24.58[22.91;26.26]	/
VL	AccPeak ($m \cdot s^{-2}$)		67.1 ± 22.91	0.64[0.48;0.78]	0.58[0.45;0.74]	34.14[32.47;35.82]	/
	iAcc (UA. s)		3.68 ± 0.77	0.7[0.57;0.82]	0.67[0.55;0.81]	20.96[19.29;22.64]	/
	MDF (Hz)	FFT	32.35 ± 5.47	0.77[0.66;0.88]	0.75[0.64;0.86]	16.91[15.24;18.59]	10
		CWT	41.36 ± 6.94	0.8[0.69;0.89]	0.8[0.71;0.89]	16.78[15.11;18.46]	10
	MNF (Hz)	FFT	43.94 ± 5.41	0.8[0.7;0.9]	0.77[0.67;0.87]	12.3[10.63;13.98]	10
		CWT	53.06 ± 6.42	0.84[0.76;0.92]	0.84[0.75;0.91]	12.1[10.42;13.78]	10
	MF (Hz)	CWT	18.89 ± 8.44	0.6[0.44;0.76]	0.51[0.38;0.69]	44.7[43.02;46.37]	/
	EnergyPeak (UA)	FFT	3.28 ± 0.96	0.69[0.56;0.82]	0.69[0.56;0.82]	29.2[27.53;30.88]	/
		CWT	2.61 ± 0.6	0.66[0.52;0.8]	0.62[0.49;0.77]	22.95[21.28;24.63]	/
	EnergyTotal (UA·s)	FFT	121.13 ± 30.83	0.71[0.58;0.83]	0.68[0.55;0.81]	25.45[23.77;27.13]	/
		CWT	130.11 ± 32.11	0.71[0.58;0.83]	0.67[0.54;0.8]	24.68[23;26.36]	/
	Damp ($m \cdot s^{-2} \cdot s^{-1}$)	CWT	22.91 ± 6.4	0.57[0.4;0.74]	0.5[0.36;0.68]	27.93[26.26;29.61]	/
	ST (s)	CWT	0.12 ± 0.03	0.47[0.32;0.67]	0.32[0.22;0.5]	26.33[24.65;28]	/

INPUT: heel impact signal; GAS: gastrocnemius medialis; VL: vastus lateralis; Acc_{Peak}: peak acceleration; iAcc: integrated acceleration; MDF: median frequency; MNF: mean frequency; MF: median frequency; ST: setting time. Damp: damping coefficient. /: never reach ICC at 0.75 within 100-steps.

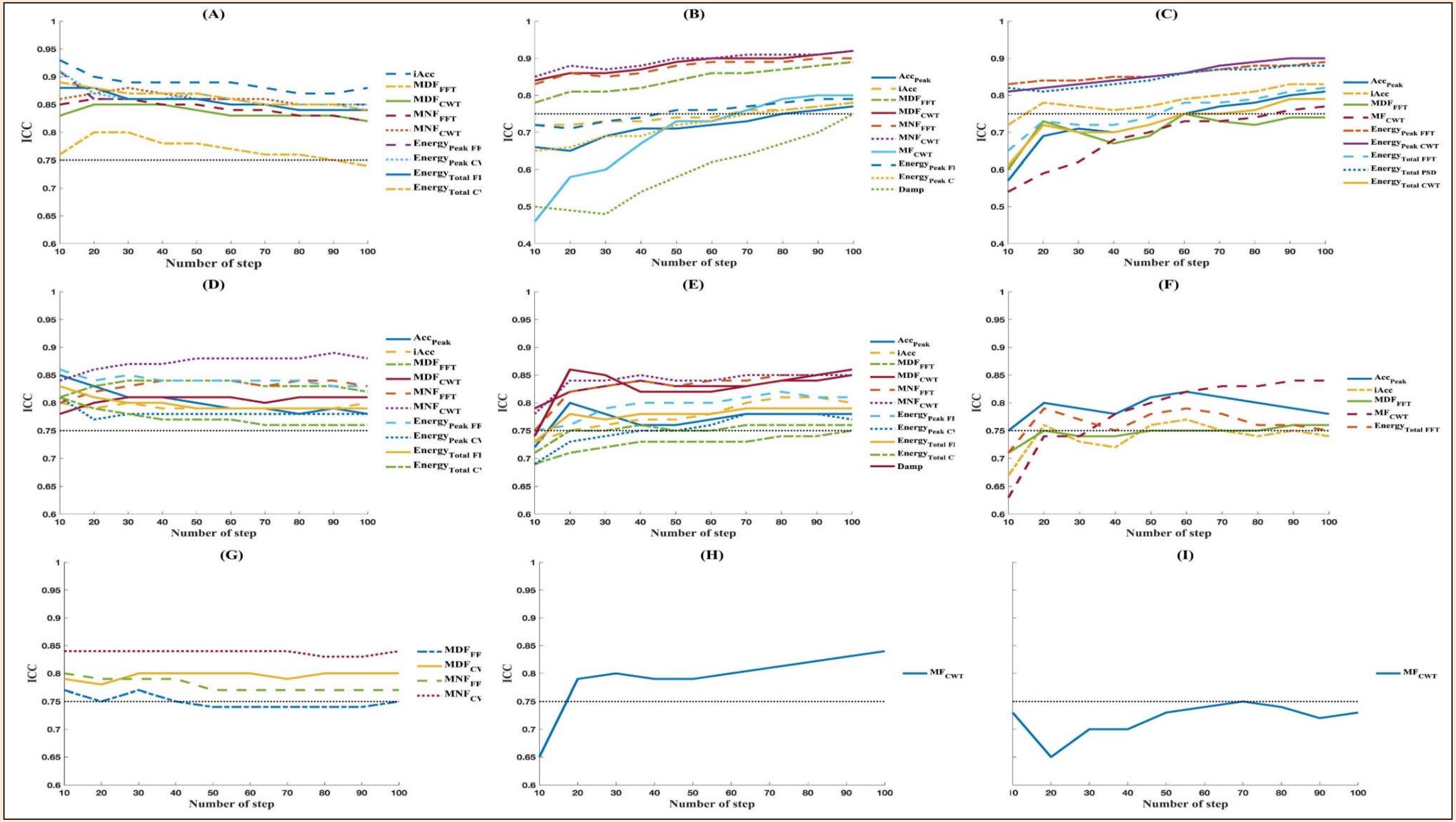

Figure 2. Intra- and Inter-day reliability of the foot impact (INPUT), soft tissue vibration (STV) of gastrocnemius medialis (GAS) and vastus lateralis (VL). From top to bottom, row 1: INPUT signal (A, B, C), rows 2: STV GAS (D, E, F), and rows 3: STV VL (G, H, I). From left to right; column1: intra-trial reliability measured on day one (A, D, G); column 2: inter-trial reliability measured on day one (B, E, H); column 3: inter-day reliability (C, F, I). The black dashed line represents the ICC value of 0.75. Acc_{Peak}: peak acceleration; iAcc: integrated acceleration; MDF: median frequency; MNF: mean frequency; MF: median frequency; ST: setting time.

Table 2. Inter-trial reliability of day one for heel impact signal and soft tissue vibration parameters.

	Variable	Method	Mean ± SD	ICCmax 95%CI	ICCmean 95%CI	CV 95%CI	N Step
INPUT	AccPeak (m·s^{-2})		178.91 ± 38.25	0.77[0.59;0.9]	0.77[0.62;0.91]	21.38[19.55;23.21]	80
	iAcc (UA. s)		4.47 ± 1.12	0.78[0.58;0.9]	0.78[0.62;0.91]	25.09[23.26;26.92]	70
	MDF (Hz)	FFT	65.71 ± 10.64	0.89[0.53;0.9]	0.89[0.76;0.95]	16.19[14.35;18.02]	10
		CWT	77.6 ± 11.31	0.92[0.63;0.93]	0.92[0.82;0.96]	14.57[12.74;16.4]	10
	MNF (Hz)	FFT	72.71 ± 8.5	0.9[0.62;0.92]	0.9[0.79;0.95]	11.69[9.85;13.52]	10
		CWT	82.34 ± 8.2	0.92[0.66;0.93]	0.92[0.82;0.96]	9.96[8.13;11.8]	10
	MF (Hz)	CWT	35.13 ± 16.9	0.8[0.53;0.88]	0.8[0.6;0.9]	48.09[46.26;49.93]	70
	EnergyPeak (UA)	FFT	3.28 ± 0.91	0.79[0.58;0.9]	0.79[0.64;0.92]	27.86[26.03;29.69]	50
		CWT	2.5 ± 0.81	0.78[0.56;0.89]	0.78[0.61;0.91]	32.32[30.49;34.16]	70
	EnergyTotal (UA·s)	FFT	260.08 ± 67.38	0.67[0.47;0.87]	0.67[0.47;0.87]	25.91[24.08;27.74]	/
		CWT	260.7 ± 66.01	0.71[0.54;0.89]	0.71[0.54;0.89]	25.32[23.49;27.15]	/
	Damp (m·s^{-2}·s^{-1})	CWT	43.93 ± 9.35	0.75[0.52;0.88]	0.75[0.52;0.88]	21.29[19.45;23.12]	100
	ST (s)	CWT	0.07 ± 0.01	0.66[0.36;0.83]	0.66[0.36;0.83]	15.75[13.91;17.58]	/
GAS	AccPeak (m·s^{-2})		64.46 ± 17.75	0.8[0.7;0.93]	0.78[0.59;0.9]	27.54[25.71;29.37]	20
	iAcc (UA. s)		3.56 ± 0.63	0.81[0.62;0.91]	0.8[0.63;0.91]	17.63[15.8;19.47]	20
	MDF (Hz)	FFT	33.07 ± 5.39	0.75[0.5;0.88]	0.75[0.5;0.88]	16.31[14.48;18.14]	100
		CWT	42.51 ± 7.82	0.85[0.54;0.9]	0.85[0.68;0.93]	18.38[16.55;20.22]	10
	MNF (Hz)	FFT	44.5 ± 5.23	0.86[0.49;0.89]	0.86[0.7;0.93]	11.75[9.91;13.58]	10
		CWT	54.09 ± 7.04	0.85[0.52;0.9]	0.85[0.69;0.93]	13.01[11.18;14.85]	10
	MF (Hz)	CWT	18.47 ± 6.13	0.42[0.13;0.73]	0.42[0.13;0.73]	33.2[31.37;35.03]	/
	EnergyPeak (UA)	FFT	3.16 ± 0.78	0.82[0.51;0.89]	0.81[0.61;0.91]	24.73[22.9;26.56]	10
		CWT	2.5 ± 0.52	0.78[0.6;0.91]	0.77[0.6;0.9]	20.66[18.83;22.49]	40
	EnergyTotal (UA·s)	FFT	118.14 ± 25.94	0.79[0.65;0.92]	0.79[0.61;0.91]	21.96[20.13;23.79]	20
		CWT	128.42 ± 28.21	0.76[0.56;0.89]	0.76[0.55;0.89]	21.97[20.14;23.8]	20
	Damp (m·s^{-2}·s^{-1})	CWT	23.41 ± 5.63	0.86[0.7;0.93]	0.86[0.68;0.93]	24.04[22.21;25.87]	20
	ST (s)	CWT	0.12 ± 0.02	0.55[0.21;0.77]	0.55[0.2;0.77]	16.86[15.03;18.7]	/
VL	AccPeak (m·s^{-2})		68.89 ± 22.98	0.28[;0.07;0.63]	0.28[;0.07;0.63]	33.34[31.51;35.18]	/
	iAcc (UA. s)		4 ± 0.7	0.63[0.42;0.85]	0.63[0.42;0.85]	17.42[15.58;19.25]	/
	MDF (Hz)	FFT	29.67 ± 5.27	0.73[0.48;0.87]	0.73[0.48;0.87]	17.77[15.93;19.6]	/
		CWT	39.49 ± 5.98	0.62[0.32;0.81]	0.61[0.31;0.81]	15.15[13.31;16.98]	/
	MNF (Hz)	FFT	40.43 ± 5.41	0.57[0.23;0.78]	0.57[0.23;0.78]	13.39[11.55;15.22]	/
		CWT	50.64 ± 6.48	0.5[0.16;0.74]	0.5[0.16;0.74]	12.8[10.96;14.63]	/
	MF (Hz)	CWT	17.3 ± 6.03	0.84[0.58;0.9]	0.84[0.67;0.92]	34.85[33.01;36.68]	20
	EnergyPeak (UA)	FFT	3.86 ± 0.91	0.66[0.42;0.85]	0.66[0.42;0.85]	23.53[21.7;25.37]	/
		CWT	2.91 ± 0.59	0.56[0.28;0.8]	0.56[0.28;0.8]	20.22[18.39;22.05]	/
	EnergyTotal (UA·s)	FFT	125.56 ± 32.21	0.43[0.12;0.73]	0.43[0.12;0.73]	25.65[23.82;27.49]	/
		CWT	133.98 ± 33.22	0.39[0.1;0.72]	0.39[0.1;0.72]	24.79[22.96;26.62]	/
	Damp (m·s^{-2}·s^{-1})	CWT	17.16 ± 5.38	0.47[0.09;0.72]	0.45[0.07;0.71]	31.33[29.5;33.17]	/
	ST (s)	CWT	0.14 ± 0.02	0.57[0.24;0.78]	0.57[0.24;0.78]	17.53[15.7;19.36]	/

INPUT: heel impact signal; GAS: gastrocnemius medialis; VL: vastus lateralis; Acc_{Peak}: peak acceleration; iAcc: integrated acceleration; MDF: median frequency; MNF: mean frequency; MF: median frequency; ST: setting time. Damp: damping coefficient. /: never reach ICC at 0.75 within 100-steps.

This increased variability could create problems when attempting to test subjects before and after a race in an ecological situation when participants need to be re-equipped after the exercise. In this case, the decrease in reliability presents a problem because the differences induced by race will have to be very marked to become observable. This situation would mainly affect the vibration energy parameters of the VL muscle.

Regarding the inter-day comparison, the number of STV parameters with good reliability continues to decrease compared to the intra-day reliability. Indeed, only 64% of the INPUT parameters, 53% of the GAS STV parameters, and 1 STV parameter of the VL reached a good reliability level. More interestingly, 13 STV parameters presented a poor inter-day reliability level, most concerning the STV parameters of the VL that 7 over 13 STV parameters with ICC less than 0.5 (Table 3). Once again, the total energy of VL STV and damping indicators for INPUT, GAS, and VL were the less reliable variables. In truth, studies examining inter-day reliability often report reduced ICC. As mentioned earlier, the fact that reliability declines from one day to the next can be explained by the fact that reequipping the subjects with the same sensor's location and cohesive band pressure is almost impossible. This may be amplified by the human coordination variability, which may induce different impacts and vibrations caused by variations in fitness and mild diffuse pain. It may also be possible that the runners produce different lower-limb movement patterns (i.e., kinetic and kinematic parameters) without being able to feel or verbalize it (Sundström et al., 2021). Previous research has shown that the soft-tissue vibration in the running was affected by the underlying internal mechanical properties of the tissues (muscle fat, connective tissue, vascular components, coupling between tissues, muscle activation, etc.) (Boyer and Nigg, 2004; Wakeling et al., 2002) and the interaction between the external factors (GRF, running velocity, foot strike pattern, angular velocity, surface and shoe type, etc.) (Ahn et al., 2014; Boyer and Nigg, 2007; Fu et al., 2013) and those tissue properties (Wakeling and Nigg, 2001b). Considering the participant in the present study were recreational runners, it could be supposed that each runner may have adopted a unique running style that could contribute to increases in inter-subject variability for some biomechanical variables of running as mentioned above; thus, it is customary to observe high CV for STV parameters. Comparing muscle vibrations over several days of manipulation seems more challenging, and interpreting the results should be cautious.

Table 3. Inter-day reliability of day one for heel impact signal and soft tissue vibration parameters. INPUT: heel impact signal; GAS: gastrocnemius medialis; VL: vastus lateralis; Acc_{Peak}: peak acceleration; iAcc: integrated acceleration; MDF: median frequency; MNF: mean frequency; MF: median frequency; ST: setting time. Damp: damping coefficient. /: never reach ICC at 0.75 within 100-steps.

	Variable	Method	Mean ± SD	ICCmax 95%CI	ICCmean 95%CI	CV 95%CI	N Step
INPUT	AccPeak ($m·s^{-2}$)		177.04 ± 41.68	0.81[0.52;0.88]	0.81[0.62;0.91]	23.54[21.71;25.37]	60
	iAcc (UA. s)		4.43 ± 1.03	0.83[0.57;0.9]	0.83[0.66;0.92]	23.34[21.5;25.17]	20
	MDF (Hz)	FFT	65.99 ± 9.78	0.75[0.51;0.88]	0.74[0.5;0.88]	14.83[12.99;16.66]	60
		CWT	78.03 ± 10.2	0.74[0.51;0.88]	0.69[0.42;0.85]	13.07[11.24;14.9]	/
	MNF (Hz)	FFT	73.04 ± 7.52	0.71[0.46;0.86]	0.69[0.42;0.85]	10.29[8.46;12.13]	/
		CWT	82.62 ± 7.49	0.7[0.43;0.85]	0.59[0.28;0.8]	9.06[7.23;10.9]	/
	MF (Hz)	CWT	35.35 ± 18.49	0.77[0.53;0.89]	0.77[0.54;0.89]	52.32[50.48;54.15]	90
	EnergyPeak (UA)	FFT	3.27 ± 0.82	0.89[0.64;0.92]	0.89[0.77;0.95]	25.1[23.26;26.93]	10
		CWT	2.49 ± 0.75	0.9[0.6;0.91]	0.9[0.8;0.96]	30.03[28.2;31.86]	10
	EnergyTotal (UA·s)	FFT	261.68 ± 78.48	0.82[0.56;0.89]	0.82[0.63;0.91]	29.99[28.15;31.82]	60
		CWT	261.11 ± 74.91	0.79[0.52;0.88]	0.79[0.59;0.9]	28.69[26.85;30.52]	60
	Damp ($m·s^{-2}·s^{-1}$)	CWT	45.56 ± 8.77	0.7[0.42;0.85]	0.7[0.42;0.85]	19.25[17.42;21.09]	/
	ST (s)	CWT	0.07 ± 0.01	0.18[;0.21;0.53]	0.17[;0.22;0.52]	14.28[12.45;16.12]	/
GAS	AccPeak ($m·s^{-2}$)		72.33 ± 25.75	0.82[0.5;0.89]	0.78[0.56;0.89]	35.6[33.76;37.43]	10
	iAcc (UA. s)		4.11 ± 0.72	0.77[0.53;0.88]	0.74[0.5;0.87]	17.63[15.79;19.46]	20
	MDF (Hz)	FFT	29.23 ± 4.38	0.76[0.52;0.88]	0.76[0.54;0.89]	14.99[13.16;16.83]	20
		CWT	38.35 ± 5.19	0.43[0.06;0.7]	0.29[;0.1;0.61]	13.52[11.69;15.36]	/
	MNF (Hz)	FFT	39.54 ± 4.12	0.44[0.07;0.7]	0.43[0.06;0.7]	10.42[8.59;12.25]	/
		CWT	49.43 ± 5.54	0.25[0.14;0.42]	0.15[0.02;0.24]	11.21[9.38;13.04]	/
	MF (Hz)	CWT	16.7 ± 5.63	0.84[0.56;0.89]	0.84[0.68;0.93]	33.73[31.89;35.56]	40
	EnergyPeak (UA)	FFT	4.07 ± 0.96	0.72[0.46;0.86]	0.69[0.42;0.85]	23.56[21.73;25.39]	/
		CWT	3.03 ± 0.65	0.74[0.49;0.87]	0.7[0.43;0.85]	21.55[19.72;23.38]	/
	EnergyTotal (UA·s)	FFT	129.06 ± 34.13	0.79[0.58;0.9]	0.75[0.52;0.88]	26.45[24.61;28.28]	20
		CWT	137.16 ± 34.15	0.62[0.32;0.81]	0.59[0.27;0.79]	24.9[23.06;26.73]	/
	Damp ($m·s^{-2}·s^{-1}$)	CWT	16.81 ± 5.33	0.32[;0.11;0.65]	0.19[;0.21;0.54]	31.72[29.88;33.55]	/
	ST (s)	CWT	0.15 ± 0.03	0.47[0.11;0.72]	0.47[0.11;0.72]	17.79[15.96;19.63]	/
VL	AccPeak ($m·s^{-2}$)		76.09 ± 51.06	0.28[;0.11;0.6]	0.18[;0.22;0.53]	67.08[65.24;68.91]	/
	iAcc (UA. s)		3.93 ± 1.68	0.26[;0.14;0.58]	0.17[;0.22;0.52]	42.66[40.83;44.5]	/
	MDF (Hz)	FFT	33.9 ± 5.75	0.68[0.4;0.84]	0.68[0.4;0.84]	16.96[15.12;18.79]	/
		CWT	42.96 ± 7	0.67[0.39;0.84]	0.67[0.39;0.84]	16.3[14.47;18.13]	/
	MNF (Hz)	FFT	45.27 ± 6.09	0.6[0.28;0.8]	0.6[0.28;0.8]	13.45[11.62;15.29]	/
		CWT	54.35 ± 6.88	0.6[0.28;0.8]	0.58[0.26;0.79]	12.67[10.83;14.5]	/
	MF (Hz)	CWT	18.68 ± 7	0.75[0.51;0.88]	0.73[0.48;0.87]	37.46[35.63;39.3]	70
	EnergyPeak (UA)	FFT	3.56 ± 1.75	0.32[;0.07;0.63]	0.2[;0.2;0.54]	49.02[47.19;50.85]	/
		CWT	2.87 ± 1.45	0.22[;0.18;0.55]	0.13[;0.26;0.49]	50.7[48.87;52.53]	/
	EnergyTotal (UA·s)	FFT	135.15 ± 73.88	0.23[;0.17;0.56]	0.15[;0.24;0.51]	54.65[52.82;56.49]	/
		CWT	148.62 ± 89.3	0.19[;0.23;0.55]	0.13[;0.26;0.49]	60.06[58.23;61.89]	/
	Damp ($m·s^{-2}·s^{-1}$)	CWT	24.14 ± 6.52	0.71[0.4;0.88]	0.52[0.11;0.78]	26.8[24.97;28.63]	/
	ST (s)	CWT	0.11 ± 0.03	0.25[;0.14;0.58]	0.25[;0.14;0.58]	22.89[21.06;24.73]	/

INPUT: heel impact signal; GAS: gastrocnemius medialis; VL: vastus lateralis; Acc_{Peak}: peak acceleration; iAcc: integrated acceleration; MDF: median frequency; MNF: mean frequency; MF: median frequency; ST: setting time. Damp: damping coefficient. /: never reach ICC at 0.75 within 100-steps.

Furthermore, it's interesting to observe that the number of steps to achieve good reliability depends on the accelerometers' location, STV parameters, and comparison. In line with the previous findings, it is not surprising that most of the STV parameters have good to excellent intra-trial reliability after only 10-steps (Arnold et al., 2019; Lavcanska et al., 2005; Oliveira and Pirscoveanu, 2021; Riazati et al., 2019; Riley et al., 2008). In contrast, almost half of STV parameters required more steps (range 50-90) to reach good inter-trial reliability compared to intra-trial reliability. As mentioned above, the artificial factor (e.g., accelerometers equipped/reequipping, re-adaptation of running gait) could affect the reliability level of STV parameters and the number of steps to achieve good reliability. In particular, the reliability of some STV parameters reveals an unstable trend (i.e., MNF_{FFT} of intra-trial reliability both for INPUT and VL) varying in an unpredictable situation. Consequently, it is worth paying particular attention to checking the reliability of these STV parameters according to the number of steps within different trials/days, which permitted the researcher to acquire the minimal steps to reach a good reliability level of STV.

Meanwhile, this study suffers from some limitations. Firstly, the current results are only relevant for treadmill running studies and, therefore, cannot be applied to other surfaces and may not be ideal for describing running conditions. Secondly, the runners performed running at a constant submaximal velocity with the different running shoes, which didn't report the influence of the running speed and shoe type on the STV reliability. Thirdly, it may be interesting to analyze the particular category population (e.g., elite runners, the overweight, and sex, the runner of different ages) because the STV measurement may be greatly affected by the mechanical properties of soft tissue. Further research should also look to quantify the kinematic, kinetic variations, high running speed, and neuromuscular changes associated with modifications in vibration parameters.

Conclusion

Present results show the good to excellent reliability of the assessment of foot impact signal and STV of the lower limb muscles measured on the same day. In contrast, comparing two days of experimentation shows that only the foot impact signal and the GAS STV remain good or correct reliability; thus, it remains challenging to measure the VL STV between the trial and days. More importantly, the reliability level depended on the number of steps to achieve variable stability. Consequently, from a practical point of view, the findings suggest optimizing experimental protocol in STV measurement during treadmill running and standardizing minimum steps requirements for appropriate STV comparison achieved from different trials/days.

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Key points

- The input signal parameters of foot impact revealed good to excellent reliability within different trials/days.
- The gastrocnemius medialis indicated more parameters of soft tissue vibration in good reliability than the vastus lateralis, and the parameters of soft tissue vibration were reduced significantly within different days.
- A minimal number of steps within different trials/days should be checked, permitting to reach a good reliability level of soft tissue vibration.

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