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Electromyographic frequency spectra analysis to investigate influence of flip flop footwear on leg muscles during flexed knee heel rise task

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***Abstract*---**Context: Contemporary wide variety of footwear is one of the main reason for increased incidence of Achilles Tendon Disorders (ATDs). Introduction: Flexed knee heel rise (FKHR) task is exploited clinically to evaluate and rehabilitate Soleus (SOL) muscle. FKHR is done in variable footwear without considering its influence on muscles. Information is lacking about footwear influence on leg muscles in FKHR. This understanding is vital for clinical efficacy. Aim – to investigate Flip Flop (FF) influence on Electromyographic (SEMG) activity of Soleus, Tibilais Anterior (TA) & Gastrocnemius lateral (GML) during FKHR. Settings and Design: within-subject cross-sectional study was performed acquiring SEMG data from 40 young healthy (male/female) individuals for SOL, TA & GML. Methods and Material: Subjects performed dominant side FKHR in FF and barefoot (BF). SEMG signals were processed for Mean Frequency (MNF) for the instant of heel rise during FKHR. Statistical analysis: MNF data was normalized (nMNF). Averaged nMNF data was dependent variable; to which paired samples t-test was applied for significance testing. Results: nMNF for SOL, TA & GML was observed higher in FF (SOL: FF - 99.01 ± 9.1, BF - 97.26 ± 9.5; TA: FF - 103.49 ± 12.9, BF - 101.32 ± 11.9 & GML FF - 103.24 ± 9.1, BF - 101.13 ± 8.9; p value <

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0.05). Discussion: As hypothesized, FF invoked more muscle activity in the investigated muscles. Shifting SEMG spectra towards higher side is an evident source of fatigue / injury (ATDs). Conclusion: Flip Flop strategically alters motor pattern & activity potentially detrimental to foot.

***Keywords*---**Soleus, Electromyography, Footwear, heel-rise, Flip Flop, Tibilais Anterior & Gastrocnemius lateral.

Introduction

Soleus (SOL) is an important foot plantar flexor with specific dominance in heel rise action when knee is kept in flexion[1, 2]. Owing to this special biomechanical property of Soleus, flexed knee heel rise (FKHR) task / test is exploited in a variety of clinical situations mainly to evaluate Soleus Muscle strength (endurance) and selective rehabilitation of Soleus Muscle especially in Achilles Tendon disorders (ATDs). Environmental conditions (especially footwear) while practicing FKHR task are highly variable with no mention / consideration of their potential effect on efficacy of the task. Despite universal acceptance of FKHR task systematically established quantified evidence about influence of Flip flop footwear (surface) on performance of this task is yet not available. Such information is required for standardization[3] of technique of FKHR task and graduation of its difficulty level. Investigating influence of flip flop (surface) effect on biomechanics of plantar flexion is pertinent for both fundamental knowledge and applied (clinical) purposes. Surface Electromyography (SEMG) is a commonly employed method to acquire quantitative information about muscle activity which is directly relatable to mechanical (kinesiological) events of muscle action. The SEMG studies are found quite reliable and valid under diverse experimental and clinical settings. With the advent of wireless & miniature SEMG sensors such studies are quite closer to real life situations with minimal impediment to the motion under investigation. Several SEMG features have been explored in previous studies, Root Mean Square (RMS), Power Spectral Density (PSD), Mean Frequency (MNF), Median Frequency (MDF), Rise time (RT) are some notable ones with credible support in their advocacy. In general frequency domain features are more found to be more robust[4] ; MDF and MNF are two such features[5] that are commonly used for investigating Fatigue and motor unit recruitment Pattern[6]. It is evident from literature that there is direct correlation between muscle force and values of both MNF & MDF[7-14]. It has also been found that calculation of MNF perform better in terms of accuracy as MDF is more affected by the ambient noise and contamination. So far no study has focused on exploring electromyographic analysis of foot-footwear interaction and its implications on Soleus (SOL) along with Tibilais Anterior (TA) & Gastrocnemius Lateral (GML) muscles in smooth execution of FKHR task. From clinical viewpoint such a study would highlight direct effect of environmental conditions (footwear/ surface) on heel rise biomechanics. Clearer understanding of such tasks could be useful for Physiotherapists / Orthopaedicians (clinicians) who rely on FKHR for both diagnostic and rehabilitative purposes in ATDs and similar problems.

The background pursuit of this study was to see if there is any acute effect of flip flop (FF) footwear on performance and behavior of soleus in plantar flexion as compared to bare foot (BF). Should we assume more muscular effort by such muscles in case of flip flop conditions than barefoot to compensate the elastic properties of sole of flip flop. Will such compensatory changes relay in Gastrocnemius Lat. (agonist) and / or Tibilais Anterior (antagonist) too? Experimental approach was adopted to find out reasonable answers to the mentioned quests. Therefore the objective of this study was to investigate any change in SEMG activity of Soleus along with Tibilais Anterior & Gastrocnemius (Lat) muscles during FKHR in Flip Flop condition. We hypothesized an "increase in SEMG activity" for all three muscles in FF condition. Mean frequency (MNF) was chosen as outcome measure to quantify any such change under two conditions.

Subjects and Methods

Approach to the Problem

Because of the concerted muscle recruitment and complex influences of one on others in locomotion activities, isolated information about effects of flip flop on Soleus muscle behaviour was expected to be confounded. Therefore we aimed to investigate the possible electromyographic differences between barefoot and Flip Flop footwear conditions in FKHR task. FKHR is often used to evaluate and train Soleus[1,2] in common clinical practices.

Design

The study followed cross sectional within-subject experimental design, where data was collected from each subject for several successive repetitions in both experimental (FF) and control (BF) condition to investigate acute effects of Flip Flop on SEMG activity of Soleus (SOL), Tibilais Anterior (TA) & Gastrocnemius Lateral (GML) muscles during FKHR in healthy individuals.

Participants

Forty healthy subjects; 14 males and 26 females, *(Mean ± SD : Age 20.41 ± 1.3 years, with 1.60 ± 0.1 m height and weight 53.75 ± 7.8 kg, UK Foot size 6.45 ± 1.7)* participated in the study. Sample size was decided on the basis of systematic literature review[15] and an *a priori* power analysis on effect size calculated from data of preliminary trials. All participants were familiar to wearing flip flop footwear. The sample was drawn on the basis of convenience sampling. Individuals with any disease / abnormality / habit that can potentially affect performance of experimental task were excluded from recruitment. Only individuals who exhibited willingness to participate and gave informed consent were included in the study. The detailed inclusion and exclusion criteria for subject recruitment are mentioned in Table1. The recruitment and experimentation was conducted concurrently during August –October, 2021. Following recruitment participants were instructed not to consume caffeine / tobacco / alcohol / medicine (at least one night prior to the day of test) or report if they do so. The study was in accordance with Declaration of Helsinki and approved by Independent Ethical Committee of Indian Fertility Society, Approval

No. F.1/IEC/IFS/2021/No.03, Dated: 21/07/2021, and registered on Clinical Trials Registry- India (CTRI) vide trial Registration. No. CTRI/2021/08/035321.

Table 1

Inclusion criteria	Exclusion criteria
▪ Healthy, active able-bodied male and female individuals. ▪ Individuals between 18 - 25 years of age. ▪ Familiar to wearing Thong Style Flip Flop Footwear.	▪ Any Neuro-musculoskeletal condition e.g. Fracture, deformity, nerve injury, multiple sclerosis, motor neuron disease etc. ▪ Pre-existing injury / pain / Fatigue /DOMS in lower extremities ▪ Any lower limb joints insufficiency ▪ Any history of Ataxia / balance disorder or vertigo ▪ Individuals under medication for neuro-muscular pain ▪ Individuals under any such medication which have side- effects on neuro-muscular capacity of any type.

Experimental Task - Flexed Knee Heel Rise (FKHR)

Subjects performed heel rise activity while standing on dominant leg with knee maintained in flexion. The initial cues of the task were adopted from the technique as described in "Flexion Heel Rise Test[16]" the final technique of the task was decided after feedback from participants of the preliminary trials. The other leg (non-dominant) was maintained actively above the floor by the subject throughout the task. The indicative technique and events of the task along with timeline are illustrated in Table 2;

Table 2
Indicative Scheme of One Complete Trial Of Flexed Knee Heel Rise Task (FKHR)

Position No.	Position No. 1	Position No. 2	Position No. 3	Position No. 4	Position No. 5	Position No. 6	Position No. 7
Event on Timeline	1st Second	5th Second	8th Second	15th Second	18th Second	18th - 20th Second	20th Second
Event Description	Bilateral balanced standing	Progressing to Dominant side sinlgle limb standng with knee extended	Progressing to Dominant side sinlgle limb standng in knee flexed	Heel Rise of dominant side from position No. 3 With Brief isometric pause at peak	Heel down back to Position No. 3	Back to Position No. 2	Back to Position No. 1

Flip Flop Footwear (Intervention)

Thongs style Flip Flop (FF) used in the study consisted of three layered ethyl-vinyl-acetate (EVA) sole. The measurements of Flip Flop for size UK 7 were- Length: 271mm, Width: 109 mm, Weight 125 gm.

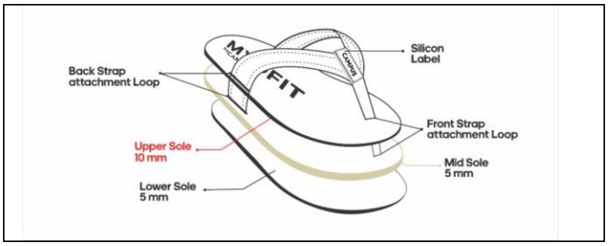


Fig - *Flip Flop Footwear*

Pre-Procedure

All subjects attended practice cum counselling session(s) for acclimatization with the FKHR Task and synchronization with the computerized commands. To equalize within subjects skills for performance of the task subjects were allowed to practice the task till the attainment of their "subjective confidence". The dominant leg side was decided by field examination for preferred leg i.e. "leg which was preferred to kick a football[17]". The experiment was preceded by observation of subject's performance of task in the actual experimental setting. Upon satisfactory performance of the task only, subjects were allowed to take part in the experiment.

Data Collection Protocol

The surface electromyographic signals were recorded using a Trigno EMG System (Delsys Inc, United States). The data was acquired using Trigno Avanti sensor's bar shaped bipolar electrodes (99.9% Ag) of 5 × 1 mm dimension, with inter-electrode distance 10 mm. The EMG acquisition was at bandwidth 20-450Hz, at ± 11 mV with amplifier gain of 300. Data collection protocol was custom designed using "Test Configuration" feature in Delsys EMGworks Acquisition software (Delsys Inc.). Three SEMG sensors synchronously captured signals from Soleus (SOL), Tibialis anterior (TA), and Gastrocnemius lateral (GML) of dominant leg, at a sampling frequency of 4000 Hz each. Location for electrode sensor placement for SEMG Data capture for Soleus (SOL), Tibialis anterior (TA), and Gastrocnemius lateral (GML), was determined by "Atlas of Muscle Innervation Zones"[18]. The sensors so placed attempted to be in line with estimated resting pennation angle. The electrode site skin preparation included shaving, cleaning and application of skin preparation (conduction) gel, as per SENIAM[19] recommendations. One additional sensor was placed on posterior heel for inertial measurement unit (IMU) data capturing only. With each electrode "Sensor" fixed on the sites appropriately, subject was asked to take position on the floor as per pre-drawn floor markings. Subject was then advised to try the FKHR task and adjust front balance support. Subjects were then asked to stand quiet to wait for computerized commands to execute the experimental trials.

Procedure

Data acquisition protocol “Test Run” was turned “ON” in the Delsys EMGworks Acquisition Software. Instructional “Audio command prompts” were sequentially generated as per the predetermined experiment workflow design of the “Test Configuration” in the Delsys software. The subjects followed these audio commands to complete the experimental Trial (Table 2). These computerized software generated voice commands ensured standardized instant and duration of different event of the FKHR task. While doing the heel rise, subjects were given “continuous feedback” to maintain knee in minimum 30^0 flexion. To assist balance subjects were allowed to touch fingers (desirably index and middle) of their pronated hand on backrest of a chair placed in front. Subjects were further instructed to actively keep the non-dominant foot above floor and touch fingers on front support only to maintain balance. The duration of one complete task trial was 20 seconds consisting of several events specified on timeline as per Table 2. First test run was arbitrarily coined “Reference Trial” which was performed bare foot. Subsequently multiple trials were performed by the subject in “Sets”. Each set consisted of two trials: one “barefoot (BF Control)” and one “Flip Flop (FF Experimental)”. The order of BF / FF conditions in each sets was randomized on the basis of “Toss of Coin”. The tests were performed on hard ceramic tiled floor. Consecutive trials were separated by an intervening rest “Washout” period to annul any physiological effect of the preceding trial(s). Sensors were checked for proper adhesion during this rest period.

SEMG Feature Extraction

Raw SEMG data was live transferred through USB cable from Delsys Trigno Avanti Base Station to a connected laptop through Delsys EMGworks Acquisition software. Thus collected raw signal data set was processed further for feature extraction. All digital signal processing and feature extraction was done by built-in calculation scripts of Delsys EMGworks analysis software. The raw SEMG signals from each muscle were corrected for DC offset, rectified after band-pass filtering by “Filter IIR” script (Butterworth IVth order; cut-off frequencies 20-450 Hz). Data was analyzed for 15th second of the 20 second data series; that corresponds to the start of heel rise activity during the test run. The Mean Frequency (MNF) was calculated from the band-pass filtered signals for 15th second of each trial.

Statistical Analysis

MNF data was exported to MS Excel for obtaining normalized MNF (nMNF) to express each MNF value in terms of % of MNF of Reference trial. Normalized MNF value of each trial for 15th second were taken as dependent variables for statistical analysis and significance testing. Further Statistical analysis were done by SPSS statistical software. nMNF Data set was tested for normality (Gaussian Distribution). The data was found largely to be parametric, hence paired samples t-test was applied to test significance of difference in observed means of nMNF for corresponding Barefoot and Flip Flop Trials. The significant level was set a priori at $\alpha = 0.05$.

Results

The normalized Mean Frequency (nMNF) of Soleus (SOL) muscle was observed to be higher in flip flop condition (*mean ± SD; 99.01 ± 9.1*) than barefoot condition (*mean ± SD; 97.26 ± 9.5*)

The normalized Mean Frequency (nMNF) of Tibialis Anterior (TA) muscle was observed to be higher in flip flop condition (*mean ± SD; 103.49 ± 12.9*) than barefoot condition (*mean ± SD; 101.32 ± 11.9)*

The normalized Mean Frequency (nMNF) of Gastrocnemius lateral (GML) muscle was observed to be higher in flip flop condition (*mean ± SD; 103.24 ± 9.1*) than barefoot condition (*mean ± SD; 101.13 ± 8.9)*

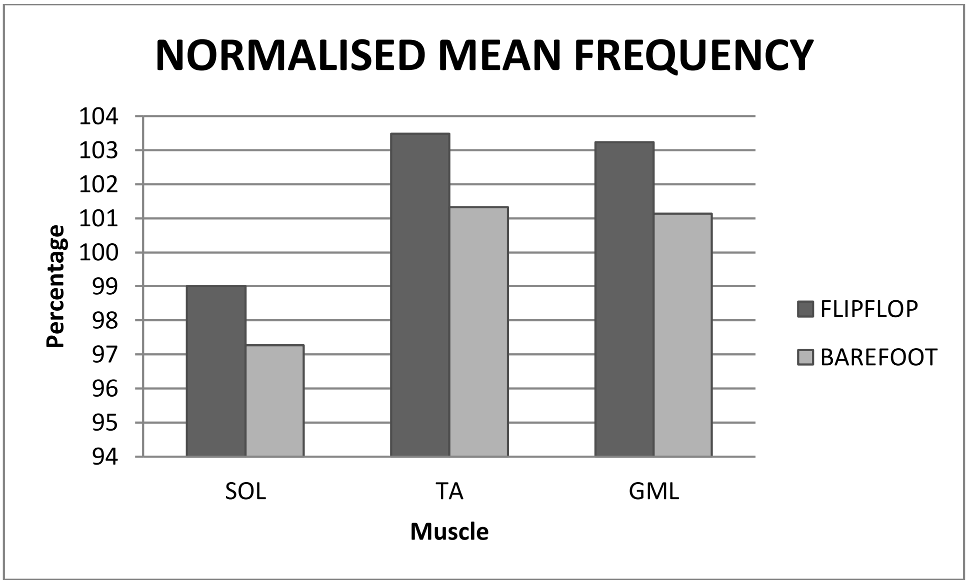
TABLE 3

Comparison groups	Dependant Variables	Paired Samples Statistics			
		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	M1_nMNF_14.5_FF_AV	99.017702	40	9.1305432	1.4436656
	M1_nMNF_14.5_BF_AV	97.269615	40	9.5998449	1.5178688
Pair 2	M2_nMNF_14.5_FF_AV	103.495460	40	12.9899120	2.0538854
	M2_nMNF_14.5_BF_AV	101.326079	40	11.9824956	1.8945989
Pair 3	M3_nMNF_14.5_FF_AV	103.240113	40	9.1094909	1.4403370
	M3_nMNF_14.5_BF_AV	101.132413	40	8.9428594	1.4139902

M1: Soleus, M2: Tibialis Anterior, M3: Gastrocnemius (LAT); nMNF: Normalized Mean Frequency; 14.5: Fifteenth Second of the data series; FF: flip Flop, BF: Barefoot; AV: Average of 3 trials

TABLE 4 - Paired Samples Test

Comparison Groups	Dependant Variables	Paired Differences					t	Df	Sig. (1-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	M1_nMNF_14.5_FF_AV-M1_nMNF_14.5_BF_AV	1.7480876	5.5644944	0.8798238	-0.0315241	3.5276992	1.987	39	0.027
Pair 2	M2_nMNF_14.5_FF_AV-M2_nMNF_14.5_BF_AV	2.1693807	8.1790377	1.2932194	-0.4464024	4.7851639	1.678	39	0.050
Pair 3	M3_nMNF_14.5_FF_AV-M3_nMNF_14.5_BF_AV	2.1077003	6.4555416	1.0207108	0.0431179	4.1722826	2.065	39	0.023



Normalized Mean Frequency (nMNF) of Tibialis Anterior in Flip flop was highest and normalized Mean Frequency (nMNF) was lowest for Soleus in Barefoot condition. Overall normalized Mean Frequency (nMNF) of Tibialis Anterior was highest and Soleus muscle was lowest for both flip flop condition as well as barefoot condition.

Discussion

This study investigated influence of Flip Flop footwear on Surface electromyographic activity of Soleus (SOL), Tibialis anterior (TA), and Gastrocnemius lateral (GML) muscles. To the best of our knowledge no study has preferentially focused on Soleus muscle behavior in flip flop shod conditions. The primary assumption at the core of this study was that flip flop would mediate neuro-mechanical consequences on Soleus muscle activity as compensatory higher effort due to its elastic (EVA) sole. Additionally it was also assumed that there will a secondary effect on GML and TA resulting in their higher activity. Overall the results are strikingly significant in the sense that all three muscles showed similar change in behavior both qualitatively and quantitatively. The take away message from the results of this study is that there is about 2% increment in MNF for all muscle in FF conditions than that of BF. As hypothesized compared to BF condition FF invoked more muscle activity in the investigated muscles. Results of present study cannot be directly compared with previous studies as diverse footwear and tasks are being studied previously with a very less commonality among the objectives and outcomes. However these results are in line with the previous work[20-23] where footwear has been concluded as a reason for changed SEMG activity in several leg muscle including SOL, TA GML Previous work has clearly attributed such changed SEMG activity to elastic properties of the sole[24] and even as precisely as elasticity in forefoot region of footwear[25], these findings are reasonably relevant and similar to present FKHR task. Besides footwear's mechanical properties there are references to its facilitated sensory feedback[26] from the plantar surface of the feet but that is largely in cases of textured soles, flip flop used in present study being plain such sensory considerations can be considered negligible thus observed changes in SEMG activity can mainly be attributed to elastic properties of flip flop sole.

In previous animal studies it has been concluded that in a mixed muscle type, the high and low frequency spectra in SEMG signals are directly related to faster (400 Hz) and slower (150 Hz) twitch fiber activity, respectively[27, 28]. The result of this study reveals that the mean SEMG frequency spectra of motor unit activity for Soleus, Tibilais Anterior & Gastrocnemius lateral (GML) muscles is in the range corresponding to slower (Type 1) twitch fiber activity. Thus it can be interpreted from here that such fibers remain of predominant role and significance in the performance of flexed knee heel rise task. Present study has further shown an increase in normalized MNF (2%) that is still in the range corresponding to Type 1 slow twitch fibers that are abundant in these three muscles. Hence it can be concluded that flip flop induced more activity of slow twitch fibers in these muscles. Another notable fact to discuss here is an observed positive linearity[29] between MNF and Motor Unit Action Potential (MUAP) conduction velocity. Increased activity in faster motor units has certainly shown higher frequency shifts in SEMG signals[29-31] which manifest in lowered rising time of the muscle[32]. This observed tendency of shifting SEMG spectra towards higher side and consequent higher / faster activation of muscles has been reported to result in fatigue & greater risk of injury[33]. Further it can also be stated that frequency changes in SEMG signals on forceful muscle action directly manifest in MUAP conduction velocity, which finally give rise to changed energy metabolism of the muscle[34]. This strategic changed muscle behaviour is potentially due to flip flop condition; the difference in nMNF observed is though small but found statistically significant for all three muscles. These altered electro-mechanical events can potentially play detrimental role in case of more elastic footwear. Such effects can be more cumulative in cyclic movements (walking / running) where carry over effects and variable foot positions are more pronounced.

Footwear is an integral socio-cultural outfit in present times, more so it is being touted as an effective intervention and performance device especially in sports rehabilitation / training; this necessitates gaining more specific information about footwear that can be exploited for clinical benefits. From therapeutic viewpoint clinicians may take a cue from results of present study while prescribing FKHR task especially with "at risk" / ATD population" and new footwear. Practitioners attempting to introduce footwear / surface as rehabilitation modality are suggested to consider acute effects of foot-footwear interactions presented herein. There is a suggestive need for guidance on caution (until familiarization) to use new footwear or frequent change between FF/BF conditions, to avert any fatigue / injury.

Limitations - The study was done in experimental context, real world situation may have changed performance and results for similar tasks. There was variability in the knee flexion maintained by subjects as it was based upon the verbal feedback only without any other control. Task being a maximal activity, subjects could not be blinded during the data collection and were consciously "targeting" the highest possible heel rise for both conditions; this might have resulted in a very small (2%) change in muscle activity. The study investigated acute effects trading off factors like familiarization and (or) wear and tear effects that are more pronounced in chronic effect studies. The study did not take into account activity / fitness level and sports history of the subjects which might influence task performance and adjustment capacity of individuals. The study was performed during an isolated FKHR task; direct application of its findings may not be fair to the cyclic activities like gait & locomotion due to carry over effects of preceding events in latter repetitions.

Future scope

The observations of the study are notable which may provide thrust for furtherance of understanding of biomechanical implications of foot-footwear interactions. If similar finding are accomplished in future studies there is a potential therapeutic implication for use of footwear in ATD insufficiency rehabilitation. An extension of present study to investigate chronic (long term usage) effects may be one future course of its furtherance. Gender or age or sports / activity based comparisons may also be considered in future studies.

Conclusion

Flip Flop induces higher muscle activity in Soleus, Tibilais Anterior & Gastrocnemius lateral in flexed knee heel rise task. Mean frequency change in flip flop condition is suggestive of altered motor unit recruitment strategy. Flip flop (Elastic surface) demand more muscle force (effort) that may be a source of fatigue / injury. Caution must be observed while practicing / prescribing heel rise task especially in vulnerable cases or with elastic sole footwear (surfaces). More such studies are required to establish observed effect of flip flop footwear in the present study.

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List of Abbreviations:

Abbreviation	Definition
ATD	Achilles tendon disorders
FKHR	Flexed knee heel rise
SOL	Soleus
TA	Tibilais anterior
GML	Gastrocnemius lateral
FF	Flip flop
BF	Barefoot
MNF	Mean frequency
nMNF	Normalized mean frequency
SEMG	Surface electromyography
RMS	Root mean square
PSD	Power spectral density
MDF	Median frequency
RT	Rise time
SD	Standard. Deviation
DOMS	Delayed onset muscle soreness
IMU	Inertial measurement unit
DC	Direct current
SPSS	Statistical Package for the Social Sciences
EVA	Ethyl vinyl acetate
MUAP	Motor Unit Action Potential

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The study was in accordance with Declaration of Helsinki and was approved by Institutional Ethics Committee as per the disclosures vide trial Registration. No. CTRI/2021/08/035321 of Clinical Trials Registry- India (CTRI).