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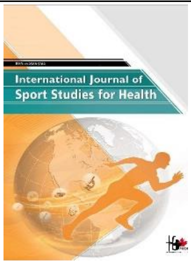

Alterations in Ground Reaction Force Frequency Content During Walking and Running in Recreational Runners with a History of COVID-19 Compared to Healthy Controls

AmirAli. Jafarnezhadgero[1], Ehsan. Fakhri Mirzanag[1*], Matteo. Zago[2]

[1] Department of Sport Biomechanics, Faculty of Educational Sciences and Psychology, University of Mohaghegh Ardabili, Ardabil, Iran
[2] Department of Biomedical Sciences for Health, Università degli Studi di Milano, Italy

*** Corresponding author email address**: amiralijafarnezhad@gmail.com

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A B S T R A C T

Objective: Despite the prevalence of chronic symptoms of COVID-19 and pathological changes that may affect gait and functional mobility in people with a history of COVID-19. No studies have investigated the ground reaction force frequency in recreational runners with history of COVID-19 differed compared to healthy controls.

Methods and Materials: The study involved 14 female adults with history of COVID-19 and 14 healthy age-matched controls. Ground reaction forces were recorded during barefoot walking (~ 1.2 m/s) and running (~ 3.2 m/s) at constant speed.

Findings: Significant differences in key frequency components in the anterior-posterior direction were observed between the COVID-19 and healthy groups during running (p=0.036). Also, Significant differences in key frequency components in the medio-lateral direction were observed between the COVID-19 and healthy groups during walking (p=0.005).

Conclusion: Lower essential number of harmonics in the medio-lateral direction during walking and higher essential number of harmonics in anterior-posterior direction during running may be attributed to decreased muscle membrane excitability, slowing of nerve conduction velocities, and axonal degeneration directly impacting skeletal muscle activation, and in turn its function.

Keywords: *Covid-19, Gait, Frequency, Kinetics.*

1. Introduction

Coronavirus disease 2019 (COVID-19) is a pandemic infectious disease that has been observed all around the world (1, 2). Individuals infected by COVID-19 often show a plethora of symptoms at cardiorespiratory (3) and the central nervous system level (4). For instance, patients with COVID-19 individuals compared with healthy controls had lower maximal oxygen uptake (3) and signs of polyneuropathy and myopathy (5). In addition, social distancing and /or quarantine result in reduced levels of physical activity, which in turn induce losses in muscle mass, strength, and power (6). In another study (7),

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researchers analyzed clinical details of 125 individuals with COVID-19 who had neurological or psychiatric effects. Of these, 62% experienced damages to the brain's blood supply, such as strokes and haemorrhages, and 31% had altered mental states, such as confusion or prolonged unconsciousness - sometimes accompanied by encephalitis (7). Intensive-care patients with severe COVID-19 showed a 30% decrease in cross-sectional area of the rectus femoris, with a reduction in thickness of the anterior compartment of the quadriceps muscle of almost 20% after 10 days (8). Taken together, COVID-19 related symptoms and with low physical activity levels may affect running and walking kinetics and muscle activities in individuals who recovered from COVID-19.

Jafarnezhadgero et al. (2022) demonstrated higher peak vertical and medial ground reaction forces (GRFs) during push-off phase in individuals with history of COVID compared with controls (9). Moreover, higher peak lateral GRFs were found during heel contact in the COVID group (9). COVID-19 individuals showed a shorter time-to-reach the peak vertical and posterior GRFs during heel contact (9). Also, in terms of muscle activity during running, the COVID group exhibited higher gastrocnemius and lower vastus medialis activities at heel contact (9). The COVID group had higher gluteus medius activity during the late stance phase and lower tibialis anterior and vastus medialis activity during the late stance phase than that healthy ones (9).

The frequency content of Ground Reaction Forces (GRF) is relevant in gait analysis as it provides crucial information about movement variability and stability, Also, it identifies differences in motor patterns across individuals with neurological disorders or post-COVID-19. In particular, information can be obtained about eventual collisions (10) or running-related injuries (11, 12). Also, GRF frequency content may be representative of frequency domain characteristics of many anatomical components such as joints, muscles, and nerves during walking (13). Furthermore, it seems that the frequency content of GRFs during gait can provide an important role in clinical treatment (11, 14). For example, 99.5% power of the GRF signal can be a measure of tremor and instability of the movement pattern (15). In that, the higher the frequency content of data, the higher the tremor and the instability. Other common variables include the frequency and the number of harmonics essential for reconstructing the GRF data at a certain accuracy level (16). Adults with knee joint disease require a lower number of harmonics than healthy peers (17), whereas children with cerebral palsy need a higher number of harmonics when reconstructing the data at 95% of the total amplitude (16). The frequency corresponding to 99% or 99.5% of the GRF total power was found to be lower in clinical populations than in healthy controls (18-20). Stergiou et al. (2002) investigated the frequency domain in older adults and found significantly lower frequency content in the anterior–posterior direction compared to the healthy young controls (21). This was attributed to decreased forward speed which is common among elderly ambulators. Giakas et al. (1996) examined the frequency domain of GRFs in scoliosis patients (22). Their study also examined common time-dependent measures. They found significantly higher frequency domain content in all three planes with the largest effect in the medial–lateral direction. They found no significant differences in the time dependent measures. This is valuable considering scoliosis is a tri-planar spinal deformity that seems to affect balance and walking in all three planes and yet common time-dependent measures could not detect any differences (22). No previous studies have examined the frequency domain of the GRFs during both walking and running activities in in individuals who recovered from COVID-19.

Thus, it is possible that frequency analysis of GRFs may be useful in individuals with history of COVID-19 as it can be used to detect relevant features in gait mechanics of these patients that could in turn reflect functional abnormalities. To the best of our knowledge, there are no studies that examined frequency content of GRFs during both walking and running in individuals with a history of COVID-19 and low-dose running rehabilitation protocol versus healthy controls. Thus, the purpose of this study was to compare GRFs frequency content in individuals with history of COVID-19 versus healthy control ones during both walking and running activities. We hypothesized that three dimensional GRFs frequency content were greater in individuals with COVID-19 compared with healthy controls during both walking and running activities.

2. Methods and Materials

2.1 Study Design and Participants

Thirty-five young recreational female runners (average weekly mileage: ~16 km) were enrolled in this study (Table 1) (23, 24). A gender-specific approach was adopted due to previously reported differences in biomechanical characteristics between females and males (25, 26). Twenty-one runners with a history of COVID-19 hospitalization volunteered to participate in this study. Seven participants were excluded following a clinical examination conducted by a cardiologist. The participants were hospitalized for about 18 days (15-23 days) and they participated in the present study after about 17 days (14-21 days) post-discharge. An inclusion criterion was the engagement in recreational long-distance running for at least 2 years prior to COVID-19 hospitalization. The average weekly mileage before the COVID infection was ~17 km. Nine participants from each group used a forefoot striking pattern while the remaining participants used a rear foot striking pattern. Participant characteristics are shown in Table 1.

Overall, disease severity at the time of hospitalization was "mild-to-moderate" for COVID-19 individuals based on the American Thoracic Society Guidelines for community-acquired pneumonia (27). COVID-19 infection was defined as a positive result on real-time reverse-transcription polymerase chain reaction analysis of throat swab specimens, and/or radiologic assessments including chest computer tomography according to the classification of the Radiological Society of North America (RSNA) (28).

Leg dominance was determined using the kicking ball test. The dominant leg was analyzed. Written informed consent was provided from all participants prior to the start of the study.

2.2 Experimental Protocol

Initially, participants performed 4 minutes of stretching and 2 minutes of warm-up in the form of jogging. Participants were asked to run and walk barefoot at a constant speed of ~3.2 m/s and 1.2 m/s over a 18-m over ground straight walkway with an embedded force plate (29). The average running and walking speed were computed by dividing the running and walking distance (i.e., 18 m) by the running and walking time which was assessed using a chronometer.

2.3 Ground Reaction Force Recordings

Vertical, medio-lateral, anterior-posterior ground reaction forces were recorded using a force plate (Bertec Corporation, Columbus, 4060–07 Model, OH, United States). The force plate recorded data at a 1,000 Hz sampling frequency. Kinetic data were analyzed during the stance phase of running and walking, defined as the interval from ground contact (vertical GRF>10 N) to toe off (vertical GRF<10 N). Kinetic data were filtered using a fourth-order low-pass Butterworth filter with a cutoff frequency of 20 Hz (determined by residual analysis) (30). All ground reaction forces were normalized to the individual's body weight (xBW).

2.4 Data analysis

The three orthogonal components of the GRF (Fx, Fy, Fz) were analyzed. Fourier analysis, as described below, was performed on the GRFs of dominant limb in all subjects. The frequency component of the greatest magnitude contained in 99.5% of the power spectrum density plot was chosen as the criterion to represent frequency content. This choice was made in order to identify subtle features of the GRFs patterns, such as the heel strike impulsive load in the vertical force, usually described by high frequency harmonics. The MATLAB program used a fast Fourier transform to extract frequency content of the GRF data (30). The detailed presentation of Fourier series of GRF can be found elsewhere (16, 22). Based on previous studies, two frequency-domain indexes were used for further analysis for the vertical, anterior–posterior, and medio-lateral GRF of each trial (21, 31). The first index was frequency with power of 99.5% (F99.5%), which indicates the frequency that has 99.5% of the signal power or, in other words 99.5% of signal power is lower than that such frequency (Eq. (1)) (32).

$$\int \int_0^{f99.5} P\,(f)\,df = 0.995 \times \int_0^{fmax} \times P(f)df \quad (1)$$

Where P is the integral power of frequency against amplitude curve, f_{max} is the maximum frequency of the signal, and P (f) is the power at frequency f (32).

According to the method described by Schneider and Chao, the second index was the essential number of harmonics (n_e) that are required to reconstruct the original data to 99.5%. This variable was defined as the number of harmonics satisfying the condition that the sum of the relative amplitudes of each harmonic over the total amplitude is less than or equal to 0.995 (Eq. 2) (33).

$$\sum_{n=1}^{n_e} \frac{\sqrt{A_n^2 + B_n^2}}{\sum_{n=1}^{m} \sqrt{A_n^2 + B_n^2}} \leq 0.995 \quad (2)$$

where n is the harmonic number, An and Bn are the Fourier coefficients. The fifth index was the amplitude of each harmonic (Hi), where i is the number of each harmonic.

2.5 Statistical analysis

Normal distribution of data was confirmed using Shapiro-Wilk test. Homogeneity of variance was examined by a Levene test. Descriptive data were expressed as mean (SD) for both groups. Independent sample Students't-test was used for statistical analysis. To calculate an effect size, Cohen's d was used: d≤0.2 was considered small, >0.8 large, and between these values moderate (34). The significance level was set at p< 0.05. All analysis were done using SPSS v. 27.

3. Results

The anthropometric characteristics of participants are presented in Table 1.

Table 1. Participant characteristics according to group allocation (m±SD).

Characteristic	Healthy group	Covid-19 group	P-value
Age (years)	23.4±1.9	22.3±1.5	0.834
Height (cm)	171.4±6.7	169.0±85	0.366
Mass (kg)	63.2±10.9	60.0±7.1	0.357
Body mass index (kg/m^2)	21.3±2.3	20.9±1.3	0.560
Weekly mileage (km)	16.2±1.8	16.3±1.5	0.941

P-values indicate between group differences in the respective parameters.

Significant differences in essential harmonics in the anterior-posterior direction were observed between the COVID-19 and healthy groups during running (P=0.036, large effect). As detailed in Table 2. No statistically significant differences were observed between groups for other variables (P>0.05).

Table 2. Mean and standard deviation of the frequency content of ground reaction force values during running.

Directions	Variables	Healthy group	Covid-19 group	P-value	Effect size
Medio-lateral	Power 99.5 %	17.40 ± 5.24	14.30 ± 4.53	0.094	0.63
	Essential number of harmonics	16.17 ± 4.28	13.92 ± 2.95	0.105	0.62
Anterior-posterior	Power 99.5 %	14.20 ± 4.28	11.47 ± 3.35	0.063	0.71
	Essential number of harmonics	19.75 ± 3.40	22.81 ± 4.15	0.036*	0.81
Vertical	Power 99.5 %	8.97 ± 2.24	8.83 ± 1.02	0.822	0.09
	Essential number of harmonics	15.37 ± 3.63	15.76 ± 2.32	0.823	0.13

Significant differences in essential harmonics in the medio-lateral direction were observed between the COVID-19 and healthy groups during walking (P=0.005, large effect). As detailed in Table 3. No other variables showed statistically significant between-group differences (P>0.05)

Table 3. Mean and standard deviation of the frequency content of ground reaction force values during walking.

Directions	Variables	Healthy group	Covid-19 group	p-value	Effect size
Medio-lateral	Power 99.5 %	15.53 ± 5.22	15.23 ± 5.01	0.874	0.06
	Essential number of harmonics	15.16 ± 2.85	12.36 ± 2.13	0.005	1.12
Anterior-posterior	Power 99.5 %	14.28 ± 3.86	14.78 ± 4.80	0.756	0.12
	Essential number of harmonics	20.93 ± 3.68	21.41 ± 4.05	0.735	0.12
Vertical	Power 99.5 %	10.00 ± 2.24	9.86 ± 3.52	0.903	0.05
	Essential number of harmonics	16.78 ± 2.69	17.85 ± 3.71	0.376	0.33

4. Discussion and Conclusion

Our results demonstrated a greater essential number of harmonics in the anterior-posterior direction in the COVID-19 group during running compared to the healthy group. The use of frequency content analysis in gait measures allows for a more comprehensive analysis of the entire walking cycle instead of discrete points or events in the cycle (14).

Neuromuscular complications, commonly acquired in intensive care units, affect approximately 40% of patients (35), and are characterized by decreased muscle membrane excitability (36). This causes a prolonged duration of the compound muscle action potential and a reduction of motor conduction velocities (36). Decreased muscle membrane excitability, slowing of nerve conduction velocities, and axonal degeneration directly impact skeletal muscle activation, and in turn its function (37). As such, it is likely that peripheral nerve damage contributes to a lower voluntary muscle activation in patients with Covid-19 (38) and may be lead to greater essential number of harmonics in the anterior-posterior direction in the Covid-19 group. However, further study is needed to better clarify this issue. Stergiou et al. reported that reduction in anterior–posterior GRFs frequency content may be due to the differences in the walking or running velocity [39]. They stated that walking and running are sagittal plane movements and speed differences will be reflected mostly in the anterior–posterior component (21). However, in the present study running speed was constant in both groups. Therefore, other factors may affect essential number of harmonics in the anterior-posterior direction in the Covid-19 group during running. It is currently unknown whether essential number of harmonics in the anterior-posterior direction, the frequency content components, the duration that signal power occurs during running, and/or some other frequency characteristic has the greatest effect on running injury development (11). Moreover, there were not statistically significant differences between groups in power 99.5 % during running. These parameters contain information about the entire waveform; with an accuracy level of 99.5% they are useful in encapsulating GRFs data without arbitrarily restricting the analysis to selected points of the force-time curves. Consistently with our results, previous studies demonstrated that vertical GRFs frequency content exhibit less variability than that in the anterior–posterior and horizontal directions (39, 40).

The number of essential harmonics in the medio-lateral direction was 22.7% lower in the Covid-19 group compared to the healthy group during walking. Moreover, there were no statistically significant between-groups differences in frequency with power of 99.5%. In the meantime, a fewer number of harmonics in the Covid-19 group implies that anatomic components with higher oscillatory frequencies, particularly in the related motor neurons and neural pathways, may not be used at the same level as in the Covid-19 group (41). The defective neuromuscular system in persons with Covid-19 group has been revealed by a delayed onset of muscle activation, predominance of co-contraction pattern, and a lack of appropriate motor preparation in motor performance (7, 8). Jafarnezhadgero et al. (2022) showed different running kinetics and muscle activities were found in COVID-19 individuals versus healthy controls. So that COVID-19 individuals showed greater peak vertical and medio-lateral GRFs during the heel contact and push-off phases and shorter time to reach peak of vertical and posterior GRFs at heel contact and greater medial gastrocnemius and lower vastus medialis activities during the early stance phase of running (9). However, there were no statistically significant differences in power 99.5% during both walking and running.

This study has limitations that should be considered while interpreting results. First, the sample size was relatively low. However, our results showed an acceptable statistical power. Second, only females included in the present study. Therefore, in principle findings could not be generalized to the males as well. Third, walking and running speed were recorded with chronometer in the present study. This method measures only the average speed and the center of mass speed during foot contact with the force plate may be different. Finally, we only evaluated frequency content of GRF data. Therefore, further study using kinematic and electromyography data were needed to better establish this issue.

Overall, our results showed COVID-19 disease could possibly affect ground reaction force frequency content while gait. These findings could be used for designing rehabilitation protocols for individuals with history of COVID-19.

Authors' Contributions

All authors equally contributed to this study.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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Declaration of Interest

The authors report no conflict of interest.

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Ethical Considerations

The study was conducted in accordance with the latest version of the Declaration of Helsinki. Ethical approval was obtained from the local ethical committee (IR.UMA.REC.1400.078).

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