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Clinical gait analysis reveals altered walking patterns in critical Covid 19 survivors

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ABSTRACT

Background: Covid-19 has dramatically increased the number of admissions in intensive care units due to respiratory complications. In some cases, the arousal of neurological impairments, such as peripheral neuropathies, have been revealed. The purpose of this research was to characterize the gait pattern and muscle activity changes in Covid-19 survivors compared to physiological gait.

Methods: Twelve post-Covid-19 participants admitted to intensive care units and twelve non-disabled controls were considered. Kinematics, kinetics and surface electromyographic data were collected for each participant during walking. Post Covid-19 participants were further divided into two sub-groups, according to the number of days spent in the intensive care units. Lower limb joint angles, moments and powers were extracted as well as the muscle activity of four muscles bilaterally, the spatial, temporal and spatiotemporal parameters of gait and the ground reaction forces. The extracted variables were compared through OneWay-ANOVA or Kruskal-Wallis tests where appropriate ($p < 0.05$).

Findings: Overall, the considered parameters revealed statistically significant reduction in gait speed, cadence, range of motion in the sagittal plane, anteroposterior and vertical ground reaction forces between pathological and control participants. Larger alterations of the gait patterns were highlighted in the post-Covid-19 group hospitalized in intensive care units longer than 35 days, where a reduced muscle activity was observed on all the analyzed muscles.

Interpretation: Results suggested that the severity of gait impairments in post-Covid-19 participants might be correlated with intensive care units-bedding period. Gait biomechanics assessment could be adopted in the clinical decision-making process to improve treatment protocols in post-Covid-19 survivors.

1. Introduction

Covid-19 significantly contributed to increase the number of admissions in intensive care units (ICU) mainly due to respiratory failure (Bansal et al., 2021; Fan et al., 2020; Ranucci et al., 2020). Persistent neurological impairments after SARS-CoV-2 infection have been also reported leading to different types of morbidity (Balcom et al., 2021; Montalvan et al., 2020; Nuzzo et al., 2021; Schirinzi et al., 2021) including peripheral nervous system disorders (Karuppan et al., 2021; Koralnik and Tyler, 2020; Mirzaei et al., 2021). Different mechanisms have been suggested to justify how Covid-19 may result in peripheral neuropathy, some authors suggested an immune reaction or vascular disorders (Spudich and Nath, 2022), others related it to the neurotoxic side effects of drugs used to treat the symptoms of Covid-19 and, to a lesser extent, due to the compression of peripheral nerves resulting from prolonged bedding in the ICU (Finsterer, 2021). However, a diagnostic test for Covid-19 specific neurological syndromes remains unclear (Balcom et al., 2021). It was proved that peripheral neuropathy can

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cause a variety of walking disorders which can affect an individual's ability to walk safely and independently (Baker, 2018; Beaulieu et al., 2018; Singh et al., 2022), however the question to what extent the neuromuscular dysfunctions associated with Covid-19 could affect the walking pattern is not yet answered. Gait analysis is the study of human walking, including the biomechanics, motor control, and sensory feedback involved (Whittle, 2014). It can be used to identify abnormalities in walking indicating neuropathy and providing important insights into the specific patterns of gait abnormalities in different pathologies. Several studies have demonstrated altered walking in individuals with diabetic peripheral neuropathy (Alam et al., 2017; Sawacha et al., 2010, 2009). Researchers have also shown through various studies the utility of assessing gait in providing clinicians with insights into their post-stroke patients' lived experiences, enriching their evaluations and plans of care (Dorsch et al., 2015; Shin et al., 2020; Wang et al., 2020). Other authors have demonstrated the importance of using gait and balance analysis to monitor the clinical progress in patients with Parkinson's disease overcoming the limited accuracy of the conventional clinical scales, adding that the precise determination of walking modifications in such patients is beneficial in determining which intervention elements are most critical in bringing about positive, clinically meaningful changes (Álvarez et al., 2020; Cole et al., 2017; Xu et al., 2018). Some of the key parameters that are commonly assessed during gait analysis in peripheral neuropathy include changes in speed, stride length, cadence, foot clearance, double support time and/or presence of gait asymmetry (Richardson et al., 2005; Tan et al., 2022). Through such parameters gait analysis can help to identify the condition, detect its severity and monitor its progression. Moreover, gait analysis is capable to distinguish minimal detectable change values of walking kinematics and kinetics (Rábago et al., 2015; Wilken et al., 2012) which in return can be of great value in evaluating the effectiveness of interventions used in physical rehabilitation protocols.

The purpose of our study was to characterize the gait pattern and muscle activity changes in post- Covid-19 patients who were admitted to ICU, compared to unaffected controls. Secondarily, we aimed to explore if the duration of admission in ICU influences the walking kinetics, kinematics and muscular activity. This work could highlight the clinical value of implementing gait analysis in monitoring patients who survived Covid-19.

2. Methods

2.1. Participants

Twelve people with a history of ICU admission secondary to Covid-19 infection (Post Covid = PC, body mass index (BMI) = 28.4 ± 5.3 kg/m2; age = 66.1 ± 6.9 years) and twelve non-disabled controls (healthy controls = HC, BMI = 25.6 ± 3.0 kg/m2; age = 63.2 ± 6.2 years) matched for age, sex and BMI were enrolled in the study following the indications for defining appropriate reference data provided by the Italian Society of Clinical Movement Analysis position paper (Benedetti et al., 2017). PC people have been hospitalized and bedded in ICU due to the worsening of the pulmonary infection. The average duration of the ICU stay was 39 days and varied per each subject within a minimum of 5 days and a maximum of 75 days. Participants of the PC have been assessed 12 months after the ICU dismission during which a rehabilitative intervention (intensive in the first period, extensive in the latter) have been delivered at the Kos Care facilities of Porto Potenza Picena (Istituto Santo Stefano) and Ancona (Villa Adria) (See Table 1 for participants anthropometrics). Clinical gait analysis has been performed when the participant was able to walk independently for the period needed to complete the laboratory walk path at self-selected speed without walking aid, as deambulatory carts or crutches. Written and informed consent was obtained prior to the study enrollment. The form was approved by the Kos Care Internal Scientific Committee.

Participants of the PC were eligible for the study if they met the following inclusion criteria: history of ICU admission, admitted to the Kos Care centers between the year 2020 and 2021. Exclusion criteria for the PC were an age above 80 years old, a BMI > of 40 kg/m2, the presence of psychiatric disorders, previous neurological pathologies (*i.e.*, Parkinosn's disease or Multiple Sclerosis), orthopedic disease at the lower limb and inability to walk without walking aids. Gait analysis was performed after a minimum time of 12 months from the date of ICU admission. Some participants of the PC were affected by preexistent comorbidities before the Covid-19 virus infection, such as diabetes mellitus (*number of people with diabetes mellitus before Covid-19 infection* = 4) and obesity (*number of people with obesity before Covid-19 infection* = 3). Five out of twelve participants of the PC were diagnosed, after the Covid-19 infection, with a polyneuropathy confirmed by needle electromyography after the ICU hospitalization.

HC were excluded from the study if they presented cardiovascular, neurological or psychiatric diseases, severe visual or auditory impairments, orthopedic diseases or previous surgery at the lower extremities, inability to walk without walking aids or pregnancy.

2.2. Data acquisition

Motion data have been acquired at the Laboratorio di Analisi del Movimento e della Postura (L.A.M.Po., length = 7 m, width = 2.5 m, height = 3 m) of the Istituto di Riabilitazione Santo Stefano, in Porto Potenza Picena, Ancona, Italy. A 6-camera stereophotogrammetric system (100 Hz, Vicon, Oxford, UK) has been used to capture the three-dimensional trajectories of spherical passive markers placed on the participant's body (anterior superior iliac, posterior superior iliac, thigh, knee, tibia, ankle, toe, and heel, bilaterally) according to the Plug-in-Gait marker set (Kadaba et al., 1990). The camera system was calibrated according to the procedure reported in the Vicon Nexus user guide (*System Preparation tools - Nexus 2.16 documentation - Vicon Help [WWW Document]*, n.d.). Synchronously, ground reaction forces were recorded with two inground force plates (1000 Hz, AMTI, USA, threshold = 20 N), and the electrical activity of eight lower limb muscles was recorded *via* an 8-channel surface electromyographic (sEMG) system (1000 Hz, ZeroWire, Aurion, Milan, Italy). The electrodes were placed bilaterally on the Tibialis Anterior, Gastrocnemius Medialis, Vastus Medialis and Biceps Femoris according to (Agostini et al., 2020) following the SENIAM guidelines (Hermens et al., n.d.) after accurately preparing the skin.

2.3. Data processing

Three right and three left gait cycles for each participant were considered. Kinematics (*i.e.*, spatiotemporal and joint angles) and kinetics parameters data were processed using Polygon (v3.5.2, Vicon). For each participant, spatiotemporal parameters according to (Armand et al., 2024; Benedetti et al., 2017) (spatial parameters: stride length, step length, and step width; temporal parameters: stride time, double

Table 1
Participants anthropometrics, time in IUC due to Covid-19 complication.

	Post Covid-19 participants (*n* = 12, males/females = 7/5)	Control Participants (n = 12, males/females = 6/6)
Age (years)	66.6 ± 7.3	63.2 ± 6.9
BMI (Kg/m^2)	27.8 ± 5.2	25.6 ± 3.0
Time in IUC due to Covid Complication (days)	39.1 ± 27.3	–

support time, single support time, cadence; spatial and temporal parameters: gait speed), joint angles (*i.e.*, pelvis tilt, obliquity and internal-external rotation angles; hip flexion-extension, ab-adduction, and internal-external rotation angles; knee flexion-extension angle; ankle plantar-dorsiflexion, inversion-eversion, and internal-external rotation angles (Root et al., 1977)), joint moments (*i.e.*, hip flexion-extension, ab-adduction, and internal-external rotation moments; knee flexion-extension, ab-adduction, and internal-external moments; ankle plantar-dorsiflexion, inversion-eversion, and internal-external rotation moments), joint powers (*i.e.*, ankle plantar-dorsiflexion power, knee flexion-extension power, and hip flexion-extension power) and the three components of the ground reaction forces (GRFs) were extracted (*i.e.*, anterior-posterior, medial-lateral and vertical GRFs). Joint moments and joint powers are calculated *via* the inverse dynamics algorithm provided in Polygon software.

Raw sEMG were segmented in the correspondent gait cycles. The sEMG signals were band pass filtered at 20–450 Hz with a double 5th-order Butterworth filter and full wave rectified. Linear envelope of each signal was obtained by low pass filtering the signal with a 4th-order Butterworth filter (5 Hz) using Matlab (v2021a, Mathworks, MA, USA) (Romanato et al., 2022).

2.4. Statistics

The spatial, temporal and spatiotemporal parameters were statistically analyzed by means of Kruskal Wallis test, the kinematics and kinetics data were analyzed through OneWay-Anova test ($p < 0.05$, SPM1D v0.4.6), after appropriately checking for normality assumption (Shapiro-Wilk test). The time series of joint angles, joint moments, joint powers, and muscle excitations were reported as mean ± 1 time the standard deviation and interpolated over 100 samples to account for gait cycle percentage using Matlab (v2021a, Mathworks, MA, USA). The two groups (PC *vs* HC) were compared using one-dimensional statistical parametric mapping where each time node was considered in the procedure ($p < 0.05$) (Pataky et al., 2015). The 12 participants in the PC were further divided into two groups; six post Covid-19 subjects who were hospitalized in ICU for >35 days (PC_{35+}), six post Covid-19 subjects who were hospitalized in ICU for <35 days (PC_{35-}). The same analysis as described above has been performed on the extracted variables considering the three groups (PC_{35+}, PC_{35-}, HC).

3. Results

Results section was divided into subsections according to the extracted variables.

3.1. Gait kinematics

In the PC group, all the considered spatial and spatiotemporal parameters of gait were statistically significantly different from the HC. When comparing the PC_{35+} with respect to PC_{35-}, step time was the only variable not showing differences between the two subgroups. Results were reported in Table 2.

Statistically significant differences between PC and HC were found in most phases of the gait cycle within the considered joint angles (Fig. 1). Specifically, PC's ankle kinematics in the sagittal plane displayed a statistically significant more plantarflexed pattern and a decreased range of motion (RoM) with respect to HC, which was highlighted even when splitting the PC in the PC_{35+} and PC_{35-} subgroups. The knee flexion-extension angle of the PC displayed a lower RoM in the loading response and swing phases, denoting a decreased ability to physiologically flex the knee. Furthermore, when focusing on the hospitalization time, the knee flexion peak in the swing phase of the PC_{35+} presented a shift towards the end of the gait cycle, reporting statistically significant differences with respect to PC_{35-}. A high variability in the PC was observed for the hip joint and pelvis in the three considered planes.

3.2. Gait kinetics

A statistically significant decrease in anteroposterior and vertical GRFs within the entire stance phase between the PC and HC was observed (Fig. 2A). The same differences were reported when splitting PC in PC_{35+} and PC_{35-} subgroups (Fig. 2B). Considering joint power, the PC_{35+} subgroup displayed a significant reduction in ankle, knee, and hip power (Fig. 2C and D).

Results on joint moments were reported in Fig. 3. Statistically significant differences between the considered groups were reported in every plane of the considered joints.

3.3. EMG

Differences in muscle activations were statistically significant mainly during the early (VL and TA, both decreased) and mid-to-final (GM, BF and TA, decreased, increased, and decreased respectively) stance phases when comparing the two groups (PC *vs* HC) (Fig. 4A). Furthermore, in HC, where increasing walking speed has been revealed, sEMG envelopes showed stronger phasicity, (*i.e.*, differences between min and max), as well as reduced times of phasic activity. Similar differences were found

Table 2
Spatial, temporal, and spatiotemporal parameters of gait reported for control subjects, the total group of post Covid participants and the two Covid-19 subgroups.

PARAMETER	PC (POST COVID-19 GROUP) (mean ± SD)	PC > 35 DAYS ICU (mean ± SD)	PC < 35 DAYS ICU (mean ± SD)	HC (HEALTHY CONTROLS) (mean ± SD)
SPEED [m/s]	0.61 ± 0.25	0.41 ± 0.14	0.81 ± 0.17	1.28 ± 0.14
	$p = 0.00008$	$p = 0.0002$		
CADENCE [step/min]	84.6 ± 13.7	72.4 ± 5.9	98.4 ± 10.6	111 ± 8.65
	$p = 0.0004$	$p = 0.0005$		
STRIDE TIME [s]	1.45 ± 0.23	1.63 ± 0.16	1.29 ± 0.18	1.08 ± 0.08
	$p = 0.0002$	$p = 0.0004$		
STEP TIME [%]	50.0 ± 0.3	49.9 ± 0.4	50.0 ± 0.2	50.1 ± 0.7
	$p = 0.56$	$p = 0.71$		
DOUBLE SUPPORT TIME [%]	31.6 ± 10.4	35.5 ± 9.5	27.8 ± 10.8	21.3 ± 3.0
	$p = 0.006$	$p = 0.02$		
SINGLE SUPPORT TIME [%]	0.45 ± 0.13	30.2 ± 6.8	30.8 ± 5.3	39.2 ± 1.9
	$p = 0.00003$	$p = 0.0001$		
STRIDE LENGTH [%]	47.4 ± 12.9	38.6 ± 11.5	56.1 ± 7.1	80.8 ± 5.6
	$p = 0.00004$	$p = 0.0002$		
STEP LENGTH [%]	23.5 ± 6.38	19.1 ± 5.5	27.9 ± 3.5	40.2 ± 2.7
	$p = 0.00001$	$p = 0.0002$		
STEP WIDTH [m]	0.24 ± 0.05	0.27 ± 0.01	0.20 ± 0.03	0.13 ± 0.03
	$p = 0.00008$	$p = 0.0006$		

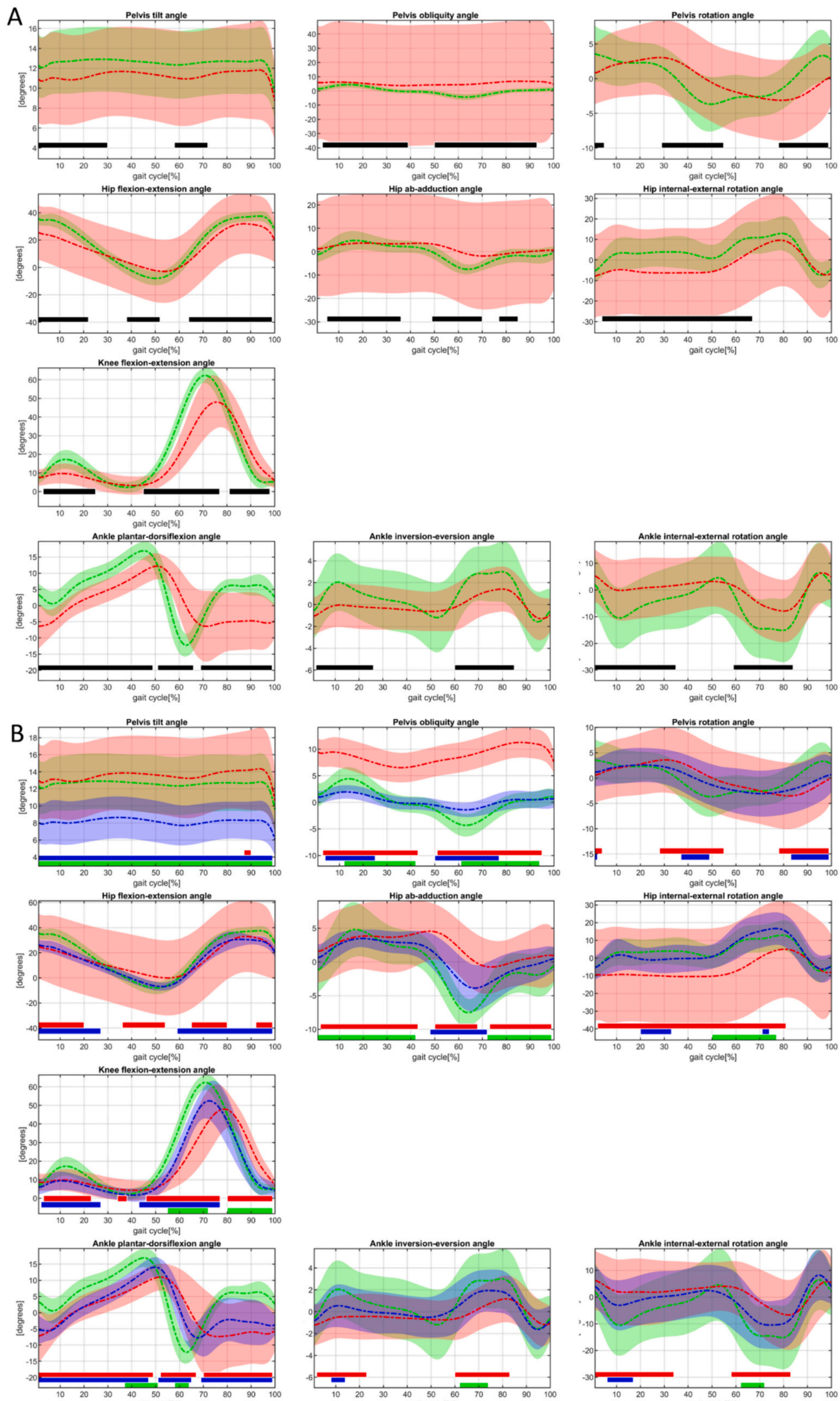

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Fig. 1. A) Joint angle bands. Mean value (dashed line) ± 1SD (shaded area). Total group of post Covid-19 participants (in red), Healthy Controls (in green). B) Joint angle bands. Mean value (dashed line) ± 1SD (shaded area). Group of post Covid-19 participants with >35 days hospitalization in intensive care unit (in red), group of post Covid-19 participants with <35 days hospitalization in intensive care unit (in blue), Healthy Controls (in green). Red horizontal bars = statistically significant differences between the healthy controls and the group of post Covid-19 participants with >35 days hospitalization in intensive care unit; Blue horizontal bars = statistically significant differences between the healthy controls and the group of post Covid-19 participants with <35 days hospitalization in intensive care unit; Green horizontal bars = statistically significant differences between the two post Covid-19 participants groups. ■ = statistically significant differences (SPM test, $p < 0.05$), in correspondence of the % of the gait cycle where the statistically significant differences were detected. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

when comparing the PC_{35+} subgroup with HC. The PC_{35-} subgroup presented a statistically significant increase in VL muscle activity during the stance phase and in GM muscle activity during the initial contact compared with HC and the PC_{35+} subgroup (Fig. 4B).

4. Discussion

Gait analysis was implemented in our study as an assessment method to explore the gait characteristics in patients who survived critical Covid-19. Our data successfully demonstrated the presence of altered walking patterns in critical Covid-19 survivors. Changes were detected in gait kinematics, kinetics, and sEMG parameters, most of which were more relevant in PC35+. To the best of our knowledge, only one study was found testing the post-Covid-19 gait spatiotemporal parameters (Keklicek et al., 2022), while no data has been published discussing the kinetic, kinematic and EMG characteristics in such patients. Furthermore, for the first time the gait alterations associated with Covid19 were pooled with respect to the ICU recovery duration to inquire about possible associated effects.

Our findings related to spatial, spatiotemporal and most of the temporal parameters indicated an altered gait in Covid-19 survivors and are in line with the study of Keklicek (Keklicek et al., 2022), where these same parameters were significantly different in a group of 12 individuals with mild-to-moderate Covid-19 history with respect to 20 sedentary controls, despite the differences between the two studies regarding the mean age of included participants, the severity level of Covid-19 infection, and the number of individuals included in the healthy control group. An excessive plantar-flexion, in association with a decreased RoM of the lower-limb joints on the sagittal plane, more evident in PC_{35+}, compared to the healthy group are justified by the alterations revealed by the kinetic parameters. Indeed, a significant reduction in the power generated by the hip, knee, and ankle joints was detected, as well as a significantly decreased GRFs, highlighting the almost absence of propulsion in post critical Covid-19 subjects. In the current study, the analysis of the electromyographic data showed statistically significant alterations in the timing of the muscle activation in the PC. Other authors, even though not directly dealing with muscle activity, demonstrated muscle weakness in long Covid-19 patients with impaired physical performance (van Gassel et al., 2021). As such, in another study by Tanriverdi (Tanriverdi et al., 2022) quadriceps weakness was observed in 35.4% of 48 participants measured using the dynamometer. Overall, our results reflected the findings of different studies regarding gait disturbances observed after full recovery from Covid-19. For instance, Pistoia and his colleagues (Pistoia et al., 2021), presented a case of gait and coordination impairment developed in a patient with positive detection of Covid-19. Another 46 years male with Covid-19 infection was presented with tremors and trouble walking (Klein et al., 2020). In addition to that, a 62 years-old male presented severe gait instability secondary to subacute cerebellar syndrome one day after the clinical resolution of symptomatic Covid-19 (Werner et al., 2021). Transverse myelitis was another unique presentation of Covid-19 demonstrated by Doukas and coauthor (Doukas et al., 2022) in a 40 years-old male, highlighting that young and otherwise healthy patients are at risk of severe Covid-19-related complications, including central nervous system disorders that in turn affects the gait pattern. Similarly, other three Covid-19 cases were presented with abnormal gait (Ben Mohamed et al., 2023; Koh et al., 2022; Lee et al., 2023). Furthermore, the walking tests included to evaluate the prevalence of impaired physical performance during gait in long Covid-19, reported similar results (Bellan et al., 2021; Tanriverdi et al., 2022; Van Den Borst et al., 2021; van Gassel et al., 2021). Abnormal gait parameters in the present study are going along with the muscle dysfunction and changes in the walking pattern detected in patients with a history of admission to the ICU for different reasons rather than Covid-19, such changes were justified secondary to ICU acquired disuse syndrome (critical illness): *i.e.*, muscle weakness at 3- and 6-months post ICU discharge, with greatest strength reductions in the ankle plantar and dorsiflexors. However, no statistically significant differences in spatiotemporal parameters were detected at 6-months after ICU discharge when compared to healthy controls (Kiriella et al., 2018). Gait speed was found to be slower in 65 years old and older adults after acute care and critical illness, regardless the small sample of the considered participants (*i.e.,* number of acute care and critical illness participants = 44, total number of study participants = 2926) (Ehlenbach et al., 2015). Our data has revealed a relationship between the duration of admission in the ICU and the altered values of walking parameters, which may suggest a correlation between prolonged bedridden secondary to critical Covid-19 and the degree of walking dysfunction, yet it does not unequivocally imply a causal relationship between the two. Nevertheless, movement disorders and peripheral neuropathy have been detected in patients shortly after mild Covid-19 with no prior history of neuropathy nor ICU admission (Abdelnour et al., 2020; Oaklander et al., 2022; Salari et al., 2021). However, in our study a group of post-ICU individuals with no prior Covid-19 infection is missing thus limiting the possibility to conclude whether the gait changes in PC individuals were secondary to critical illness or less. Even though no studies reported on joint kinematics, kinetics and sEMG in post Covid-19 survivors, similar alterations in the gait patterns can be found in other diseases associated with neuropathy. Indeed, regardless of the history of ICU admission, researchers support an association between Covid-19 and different neurological disorders such as Parkinson's Disease (PD), stroke and diabetic neuropathy. It is notable that the altered gait pattern detected in our study is more similar to the one reported in people with diabetic neuropathy rather than to people with post-stroke and PD. Diabetic neuropathic individuals frequently exhibit a conservative gait strategy where there is a slower walking speed, a wider base of gait, and prolonged double support time, sometimes associated with decreased knee RoM and pelvis obliquity. Also, a significantly higher anterior posterior GRF, a shorter step length and an altered lower limbs muscle activity has been also described compared to controls (Alam et al., 2017; Sawacha et al., 2010, 2009). These similarities between diabetic walking patterns and the gait changes detected in the present study might be related to a similar underlying mechanism (*i.e.,* peripheral neuropathy (Spudich and Nath, 2022)) which have been suggested in the literature as an explanation of such changes in both types of patients.

This study comes with several limitations that must be acknowledged. First, the effect of the walking speed was not considered when comparing the kinematics, kinetics and sEMG signals time series between the HC and PC groups. Indeed, it is worth noticing that in the state of the art some contributions can be found reporting on the dependency of gait analysis variables from gait speed (Romanato et al., 2022). It should be further considered that, a recent review and meta-analysis involving an elderly population, detected significant effect sizes in joint kinetics and kinematics only when comparison were made at faster

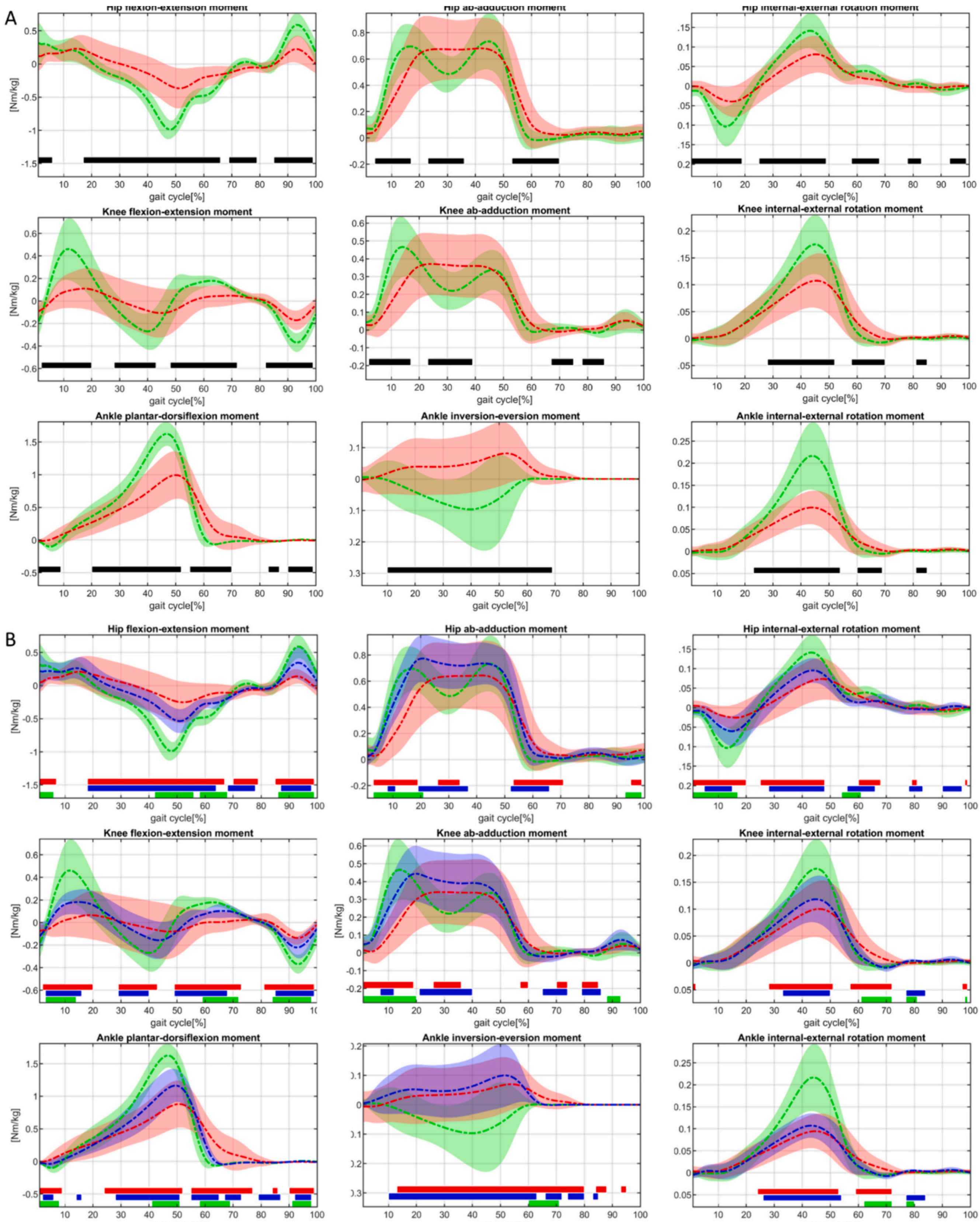

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Fig. 2. A) Ground reaction forces bands. Mean value (dashed line) ± 1SD (shaded area). Total group of post Covid-19 participants (in red), Healthy Controls (in green). B) Ground reaction forces bands. Mean value (dashed line) ± 1SD (shaded area). Group of post Covid-19 participants with >35 days hospitalization in intensive care unit (in red), group of post Covid-19 participants with <35 days hospitalization in intensive care unit (in blue), Healthy Controls (in green). Red horizontal bars = statistically significant differences between the healthy controls and the group of post Covid-19 participants with >35 days hospitalization in intensive care unit; Blue horizontal bars = statistically significant differences between the healthy controls and the group of post Covid-19 participants with <35 days hospitalization in intensive care unit; Green horizontal bars = statistically significant differences between the two post Covid-19 participants groups. C) Joint power bands. Mean value (dashed line) ± 1SD (shaded area). Total group of post Covid participants (in red), Healthy Controls (in green). D) Joint power bands. Mean value (dashed line) ± 1SD (shaded area). Group of post Covid-19 participants with >35 days hospitalization in intensive care unit (in red), group of post Covid participants with <35 days hospitalization in intensive care unit (in blue), Healthy Controls (in green). Red horizontal bars = statistically significant differences between the healthy controls and the group of post Covid-19 participants with >35 days hospitalization in intensive care unit; Blue horizontal bars = statistically significant differences between the healthy controls and the group of post Covid-19 participants with <35 days hospitalization in intensive care unit; Green horizontal bars = statistically significant differences between the two post Covid-19 participants groups. ■ = statistically significant differences (SPM test, $p < 0.05$), in correspondence of the % of the gait cycle where the statistically significant differences were detected. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

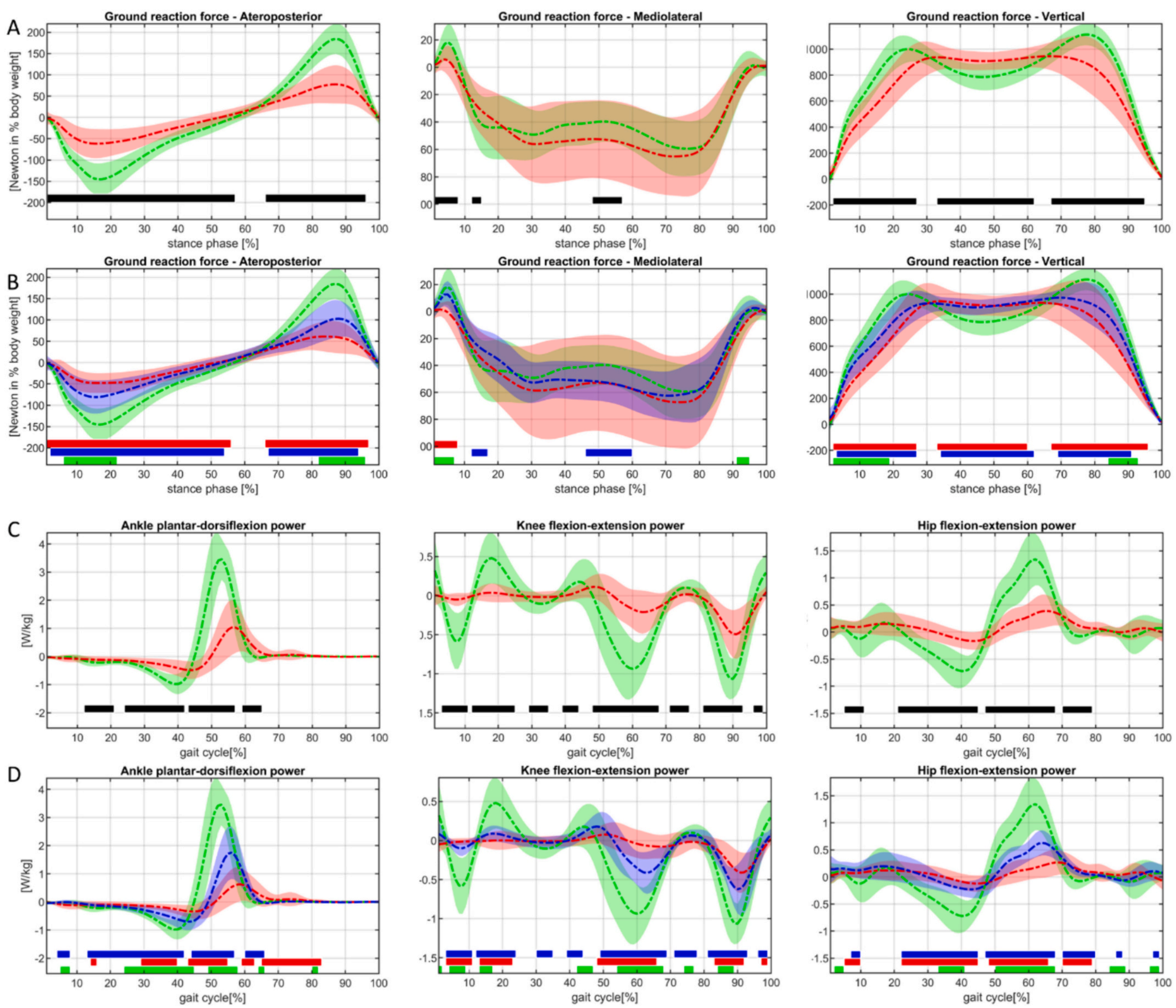

Fig. 3. A) Joint moments bands. Mean value (dashed line) ± 1SD (shaded area). Total group of post Covid-19 participants (in red), Healthy Controls (in green). B) Joint moment bands. Mean value (dashed line) ± 1SD (shaded area). Group of post Covid-19 participants with >35 days hospitalization in intensive care unit (in red), group of post Covid-19 participants with <35 days hospitalization in intensive care unit (in blue), Healthy Controls (in green). Red horizontal bars = statistically significant differences between the healthy controls and the group of post Covid-19 participants with >35 days hospitalization in intensive care unit; Blue horizontal bars = statistically significant differences between the healthy controls and the group of post Covid-19 participants with <35 days hospitalization in intensive care unit; Green horizontal bars = statistically significant differences between the two post Covid-19 participants groups. ■ = statistically significant differences (SPM test, $p < 0.05$), in correspondence of the % of the gait cycle where the statistically significant differences were detected. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

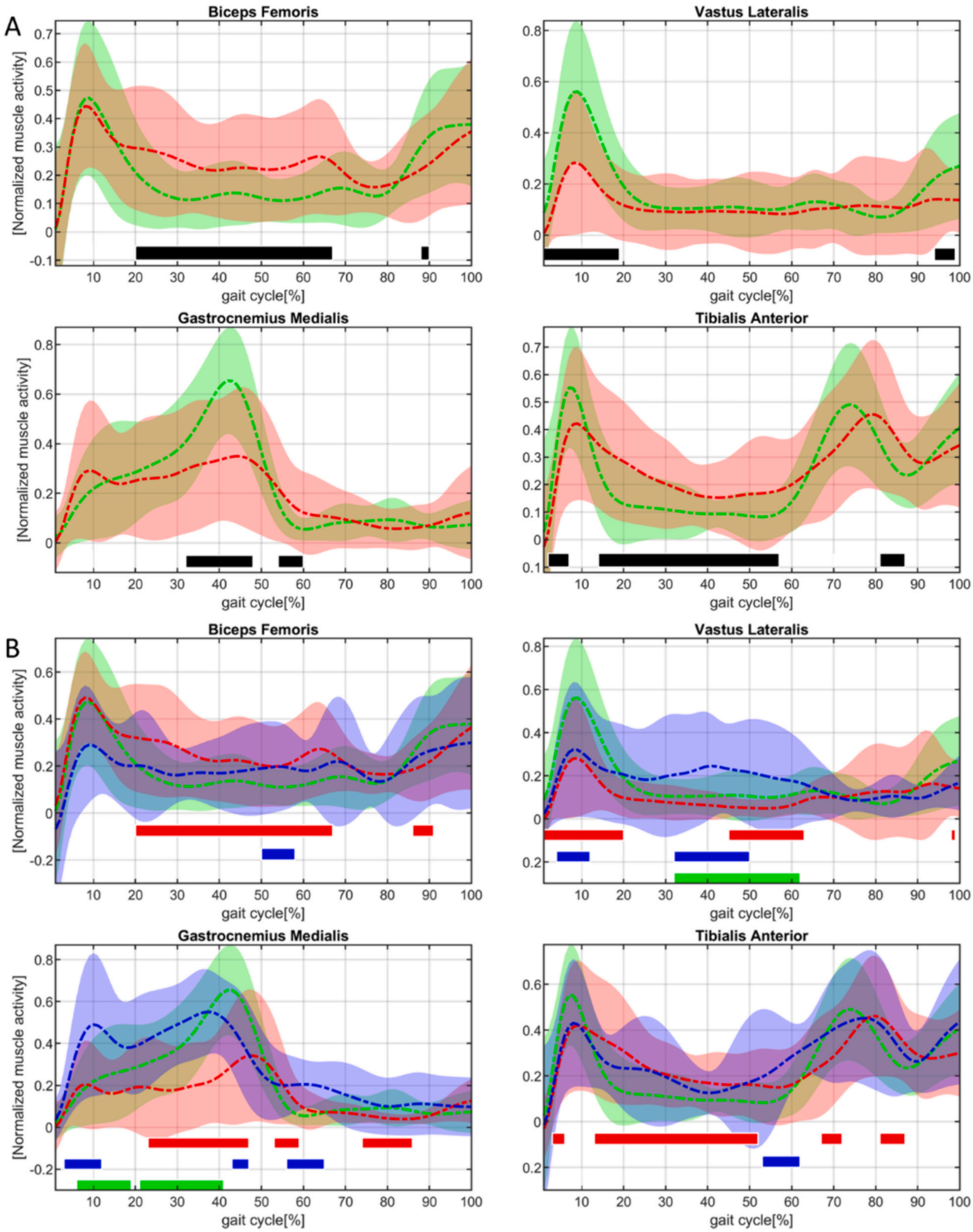

Fig. 4. A) Surface electromyography bands. Mean value (dashed line) ± 1SD (shaded area). Total group of post Covid-19 participants (in red), Healthy Controls (in green). B) Surface electromyography bands. Mean value (dashed line) ± 1SD (shaded area). Group of post Covid-19 participants with >35 days hospitalization in intensive care unit (in red), group of post Covid-19 participants with <35 days hospitalization in intensive care unit (in blue), Healthy Controls (in green). Red horizontal bars = statistically significant differences between the healthy controls and the group of post Covid-19 participants with >35 days hospitalization in intensive care unit; Blue horizontal bars = statistically significant differences between the healthy controls and the group of post Covid-19 participants with <35 days hospitalization in intensive care unit; Green horizontal bars = statistically significant differences between the two post Covid participants groups. ■ = statistically significant differences (SPM test, $p < 0.05$), in correspondence of the % of the gait cycle where the statistically significant differences were detected. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

speeds (Fukuchi et al., 2019), which is not the case of our study that compares normal self-selected speed (1.28 ± 0.14 m/s) against slow speed detected in our pathological sample (0.61 ± 0.25 m/s). Furthermore, our analysis involves time series data, while the possible effect of a dependent variable (*i.e.,* gait speed) has been reported in the literature when datasets were composed of non-continuous variables, using linear mixed-effect models (Romanato et al., 2022), to the best of the authors whenever available, a similar analysis for continuous gait analysis related time series has not shown the possibility to infer on the real effect of the dependent variable (https://spm1d.org/doc/RandomEffects.html). Therefore, our results, obtained applying the SPM1D one-way Anova function, must be interpreted taking into consideration this limitation. Nevertheless, to assess differences on the time series belonging to the two populations of interest we adopted a statistical analysis in agreement with the state of the art of biomechanical time-series comparison (Pataky et al., 2015), appositely designed to model smooth one-dimensional trajectory variance. However, with that said, the authors cannot exclude that gait speed differences between the assessed groups might have influenced our sEMG result. Indeed, as walking speeds of our groups are largely different, to substantially interpret sEMG data, walking speeds should match between groups (Hof et al., 2002). Thus, future research should consider having velocity-matched groups to provide a better interpretation of muscle activity in the assessed population. Another limitation should be considering the presence of pre-existing comorbidities displayed in the PC group which could have influenced the interpretation of the results, leaving us unable to interpret our findings in this regard. However, different studies have shown an increased prevalence of COVID-19 and poorer prognosis in older adults with cardiovascular, neurological, or respiratory preceding comorbidities (Kim et al., 2021).

The present study is the first to assess sEMG activity, gait kinetics, and kinematics in post critical Covid-19 survivors and could provide important insights into the specific gait patterns alterations associated with this pathology. More studies are needed to examine the impact of Covid-19 pandemic on community mobility and our results seem to suggest that instrumental gait analysis could be used in monitoring the progress of recovery and planning rehabilitation interventions.

5. Conclusion

Our study was able to provide important insights into the specific gait patterns of individuals who have recovered from critical Covid-19. Indeed, alterations were detected on all the analyzed parameters, namely kinematics, kinetics and sEMG, thus indicating the large impact of such a pathology on the gait of its survivors. Furthermore, larger impairments were detected in association with longer ICU recovering duration (PC_{35+}). This suggests that among the several consequences of Covid-19, gait alterations should be taken into account, and we can hypothesis that Covid-19 survivors could benefit from gait retraining.

CRediT authorship contribution statement

Asmaa Mahmoud: Writing – review & editing, Writing – original draft, Project administration, Investigation, Conceptualization. **Marco Romanato:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation. **Giulia Squartini:** Formal analysis, Data curation. **Antonio Ruggiero:** Writing – original draft, Methodology, Investigation, Data curation. **Francesco Spigarelli:** Methodology, Formal analysis, Data curation. **Antonio De Tanti:** Writing – review & editing, Visualization, Validation, Project administration. **Chiara Spagnuolo:** Writing – review & editing, Validation, Supervision, Project administration. **Zimi Sawacha:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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