



HAL
open science

Acute effects of short-term stretching of the triceps surae on ankle mobility and gait initiation in patients with Parkinson's disease

Thomas Vialleron, Arnaud Delafontaine, Isis Millerioux, Sahel Memari, Paul Fourcade, Eric Yiou

► To cite this version:

Thomas Vialleron, Arnaud Delafontaine, Isis Millerioux, Sahel Memari, Paul Fourcade, et al.. Acute effects of short-term stretching of the triceps surae on ankle mobility and gait initiation in patients with Parkinson's disease. *Clinical Biomechanics*, 2021, 89, pp.105449. <10.1016/j.clinbiomech.2021.105449>. <hal-04289733>

HAL Id: hal-04289733

<https://hal.science/hal-04289733v1>

Submitted on 22 Jul 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC BY-NC 4.0 - Attribution - Non-commercial use - International License

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20

TITLE PAGE

**Acute effects of short-term stretching of the *triceps surae* on ankle mobility
and gait initiation in patients with Parkinson’s disease**

Author names and affiliations:

**Vialleron Thomas^{1,2}, Delafontaine Arnaud^{1,2}, Millerioux Isis^{1,2}, Memari Sahel^{1,2},
Fourcade Paul^{1,2}, Yiou Eric^{1,2*}**

¹ CIAMS laboratory, University of Paris-Saclay, 91405 Orsay Cedex, France

² CIAMS laboratory, University of Orléans, 45067, Orléans, France

*Corresponding author: Yiou Eric, CIAMS laboratory, Bât 335, 91405 Orsay Cedex, France

Tel: + 33 1 69 15 31 59 Fax: + 33 1 69 15 62 22, E-mail: eric.yiou@universite-paris-saclay.fr

This manuscript is submitted as an original article (full paper). It contains 3999 words (body of the text), a 250-words abstract, along with five figures and one table.

1 **Abstract**

2 **Background.** Ankle mobility is known to be of uttermost importance to generate propulsive
3 forces and control balance during gait initiation. Impaired mobility of the postural chain
4 occurs with normal ageing and is exacerbated in patients with Parkinson’s disease. This study
5 questions whether short-term stretching session applied to the *triceps surae* improves ankle
6 mobility and, consequently, dynamical postural control in patients with Parkinson’s disease
7 performing gait initiation. **Method.** Nineteen patients with Parkinson’s disease participated in
8 this study and were randomly assigned to an “intervention group” or a “sham group”. In the
9 intervention group, patients were exposed to a 4x60 seconds *triceps surae* stretching. In the
10 sham group, they were exposed to forearm stretching. Additionally, ten age-matched healthy
11 elderly, who were not exposed to any stretching-treatment, were assigned to a “control
12 group”. Participants performed series of gait initiation on a force-plate before and after their
13 treatment. **Findings.** Ankle mobility was improved in the intervention group after *triceps*
14 *surae* stretching. The forward velocity of the center-of-mass at heel-off and motor
15 performance related-parameters (progression velocity, center-of-mass velocity at foot-contact
16 and swing phase duration) were also improved in the intervention group, with large effect
17 sizes ($d \geq 0.8$). None of the stability parameters were modified by the treatments.
18 **Interpretation.** Short-term *triceps surae* stretching is an efficient method to increase ankle
19 mobility and improve the capacity to generate forward propulsive forces in patients with
20 Parkinson’s disease. These findings are congruent with the “posturo-kinetics capacity” theory
21 according to which dynamical postural control depends on postural chain mobility.

22 **Keywords: Parkinson’s disease, Triceps surae stretching, Gait initiation, Postural**
23 **control, Posturo-kinetics capacity**

24

1 **1. Introduction**

2

3 Gait initiation (GI), the transient period between quiet standing posture and steady-state
4 walking (Brenière and Do, 1986), is a locomotor task that is widely used in the literature to
5 investigate postural control in patients with Parkinson’s disease (e.g. Bonora et al., 2017;
6 Carpinella et al., 2007; Chastan et al., 2009; Halliday et al., 1998; Mancini et al., 2009; Okada
7 et al., 2011a, 2011b). GI can be divided in two successive phases: a postural phase preceding
8 the swing heel-off, where dynamic phenomena corresponding to the so-called “anticipatory
9 postural adjustments” (APA) are generated, followed by the execution phase (Brenière and
10 Do, 1986). Along the anteroposterior axis, APA include a backward center-of-pressure (COP)
11 displacement which promotes the initial forward propulsive forces required to reach the
12 intended step length and walking speed (Brenière et al., 1987; Lepers and Brenière, 1995).
13 This postural dynamics is due to bilateral inhibition of ankle plantar-flexors activity, followed
14 by strong bilateral activation of ankle dorsi-flexors (Crenna and Frigo, 1991). Along the
15 mediolateral axis, APA include COP displacement toward the swing leg which promotes
16 center-of-mass (COM) displacement in the opposite direction, i.e., towards the stance leg.
17 This postural dynamic acts to attenuate the COM fall towards the swing leg during the
18 execution phase and therefore contributes to stability maintenance (Yiou et al., 2016a). This
19 anticipatory mediolateral COP shift has been classically attributed to the loading of the swing
20 leg associated with the activation of swing leg hip abductors (Carlsöö, 1966; Winter, 1995).
21 Recent study further reported that, the stance knee and hip are slightly flexed during APA
22 (Honeine et al., 2016) which acts to unload the ipsilateral leg and therefore complement the
23 action of swing hip abductors. EMG analysis revealed that the flexion of the stance knee is
24 favored by bilateral *soleus* silencing and a greater ipsilateral *tibialis anterior* activity with
25 respect to contralateral activity, while stance hip flexion is associated with activation of the

1 stance *rectus femoris*. Finally, during GI execution phase, the activation of the *TS* of the
2 stance leg has been shown to brake the vertical COM fall under gravity, which facilitates
3 stability maintenance after foot-contact (Honeine et al., 2014, 2013). This brief literature
4 review on the postural organization of GI thus stresses the key role of the ankle musculature
5 for balance control and motor performance (for a complete review, see (Yiou et al., 2017)).

6 This postural organization of GI is known to be altered in patients with Parkinson's disease
7 (PD). There is however no clear consensus on the effect of PD on GI at its early stage. For
8 example, Mancini et al. (2009) found that the amplitude of APA was altered in the
9 mediolateral direction, but not in the anteroposterior direction. Carpinella et al. (2007) did not
10 investigate the mediolateral APA but found that that the anteroposterior component of APA
11 was altered in early PD patients. Differences in the initial posture and/or inclusion criteria
12 may have explained these discrepancies (Mancini et al. 2009). Later in the disease, it seems
13 clear from the literature that the amplitude of both mediolateral and anteroposterior APA
14 becomes bradykinetic (Halliday et al., 1998). In addition, advanced PD patients exhibit
15 altered capacity to actively brake the COM fall (Chastan et al., 2009). These motor
16 impairments contribute to gait disorders in this population and are exacerbated in patients
17 with the freezing of gait or without medication (Mancini et al., 2020).

18 These deficits in postural control in PD patients can be envisaged from the point of view of
19 the biomechanical concept of "Posturo-kinetics Capacity" (PKC) (e.g. (Bazalgette et al.,
20 1987); for a complete review on the PKC concept, see (Bouisset and Do, 2008). According to
21 this concept, any factor that alters the dynamic mobility of the postural chain, would
22 negatively impact APA, and would therefore alter motor performance and/or stability. This
23 dynamic mobility would indeed be essential to generate the external forces required to
24 accelerate the COM during APA and brake the COM fall during the GI execution phase. This
25 concept was substantiated by recent experimental studies which investigated the relationship

1 between lower limb mobility, APA, motor performance and stability in young healthy adults
2 who are performing GI under experimental joint hypomobility induced by orthosis wore
3 (Delafontaine et al., 2018, 2017, 2015).
4 Chronical joint hypomobility or rigidity is a recurring symptom of PD (Halliday et al., 1998).
5 This rigidity is characterized by an excessive and continuous muscle tone which produces
6 stiffness and resistance to movement in joints (Raza et al., 2019). Given the above
7 considerations on the PKC concept and the brief literature review provided above, such
8 increased joint rigidity - especially of the ankle – would hinder APA development and/or
9 COM braking, and may contribute to stability impairments and slowness of movement
10 performance, which are typical motor symptoms of PD patients. In line, recent study showed
11 that the wear of a rigid ankle foot orthosis in healthy young adults induced an alteration of
12 both APA and COM braking during GI (Delafontaine et al., 2017). According to the PKC
13 concept, it can thus be expected that improving ankle mobility with specific treatments would
14 facilitate APA development and/or COM braking, with a consequent positive effect on motor
15 performance and/or stability. Ankle muscle stretching, an intervention known to increase
16 ankle mobility in healthy elderly (Gajdosik et al., 2005) and that can easily be applied by
17 patients themselves, may represent such a treatment. The present study was thus designed to
18 test the hypothesis that a short-term stretching session applied to the *Triceps surae* (TS)
19 improves ankle mobility and, consequently, the postural organization of GI in PD patients.

20

21 **2. Method**

22

23 2.1 Participants

24 Nineteen PD patients participated in this study (see table 1 for details on demographic data of
25 participants). They were randomly assigned to an “intervention group” or a “sham group”.

1 Ten age-matched healthy older adults additionally participated in this study and were assigned
2 to the “control group”. They were community dwelling seniors, free of any known
3 neuromuscular disorders and able to walk without assistance. They were included in the
4 experiment to provide normative values of dependent variables. PD patients were examined in
5 their OFF-medication state (i.e., after 12-hours withdrawal from antiparkinson’s medications,
6 as defined by Defer et al., 1999) by an experienced neuro-physiotherapist. The examination
7 was based on the Movement Disorder Society Clinical Diagnostic Criteria for Parkinson's
8 disease (Postuma et al., 2015). PD patients had no history of falling, were physically
9 independent, were able to walk without assistance, and did not experience freezing. All
10 participants gave written informed consent after being instructed about the nature and purpose
11 of the experiment, which was approved by the local ethics committee of the University of
12 Paris-Saclay. This study complied with the standards established by the Declaration of
13 Helsinki and was assigned the following trial registration number: 2018-A00162-53.

14

15 [table 1]

16

17 2.2 Ankle range of motion (ROM) assessment

18 An experienced physical therapist, who was blinded to the group assignment, measured each
19 participant's maximum passive ankle dorsiflexion in supine position, with the foot in subtalar
20 neutral position and the knee straight. This measure was made with a manual goniometer
21 (Merz Pharma, France) as it is known to be reliable for assessing ankle dorsiflexion ROM
22 (Konor et al., 2012). The axis of the goniometer was aligned with the lateral malleolus of the
23 ankle. The proximal arm was aligned with the head of the fibula. The distal arm was aligned
24 with the lateral border of the fifth metatarsal (Webber and Porter, 2010). A right angle
25 between these two arms corresponded to 0° dorsiflexion. The final position of dorsiflexion

1 corresponded to the point at which subjects felt pain or discomfort, or the experimenter
2 perceived resistance to stretch. Two measurements were taken for each leg and then averaged
3 to determine the passive dorsiflexion of each ankle (Webber and Porter, 2010). The ankle
4 dorsiflexion of both legs was assessed for each participant in the intervention and sham group
5 before and immediately after a stretching treatment (cf. below). Statistical analysis revealed
6 that the ankle dorsiflexion of the most affected side (cf. table 1) was not significantly different
7 to that of the least affected side. For clarity's sake in the report of data, values of both legs
8 were therefore pooled.

9

10 2.3 Treatment

11 In the intervention group, patients stood upright with both hands against a wall, and with both
12 feet on a wedge (20° tilt) in order to stretch their *TS*. They were instructed to slightly lean
13 forward while keeping their heels in contact with the wedge and their body aligned until they
14 felt the stretch of the calf without pain. They were then asked to maintain their posture. In the
15 sham group, patients were instructed to position their arm outstretched, palm facing the front,
16 extending their wrist and fingers by using their other hand (both arms were outstretched). In
17 both groups, series of four stretches lasting 60 seconds each were performed (Shrier and
18 Gossal, 2000). In the control group, no stretching was carried out. Participants simply stood
19 upright for the same duration as for the stretching treatments (Figure 1).

20

21 [figure 1]

22

23 2.4 Experimental task

24 Participants initially stood barefoot in a natural upright posture on a force-plate (0.9×1.80m,
25 AMTI, Watertown, USA) embedded at the beginning of a 6-meter walkway track. They

1 performed two series of ten GI: one series just before, and a second series immediately after
2 the treatment (pre-treatment and post-treatment condition, respectively; Figure 1). They were
3 instructed to initiate gait at a spontaneous velocity when they felt ready, after receiving an “all
4 set” signal, and continue walking until the end of the track. The rest time was ~10 seconds
5 between trials.

6

7 2.5 Raw Data

8 Force-plate data were low-pass filtered using a second order Butterworth filter with a 10Hz
9 cut-off frequency (Honeine et al., 2014). The mediolateral and anteroposterior coordinates of
10 the COP were computed from force-plate data. The instantaneous COM acceleration was
11 determined from the ground reaction forces according to the Newton’s second law. COM
12 velocity and displacement were computed by successive numerical integrations of COM
13 acceleration. Data were collected at a rate of 500 Hz. Data acquisition was controlled by a
14 custom-made program written in Matlab™ (Version 5.3 (R11), The MathWorks Inc., USA).

15

16 2.6 GI variables

17

18 2.6.1 *Time-events*. The following time-events were determined from the biomechanical traces
19 (Figure 2): GI onset (t_0), swing heel-off and swing foot-contact (cf. (Caderby et al., 2013), for
20 the determination of these instants; cf. Figure 2).

21

22 2.6.2 *Initial posture, APA and execution phase*. The COM position in the initial posture was
23 estimated by averaging the COP position values during the 250 ms period preceding the “all
24 set” signal. GI was divided into APA (from t_0 to heel-off) and execution phase (from heel-off

1 to foot-contact, (Brenière et al., 1987)). APA amplitude was characterized with the peak COP
2 displacement obtained during the APA time-window and the COM velocity at swing heel-off.

3

4 2.6.3 *Motor performance*. Motor performance was quantified with the anteroposterior COM
5 velocity at foot-contact, the mean progression velocity (v), with $v = [\text{step length}] / [\text{duration}$
6 of the execution phase] (Brenière and Do, 1986), step length and execution phase duration.

7

8 2.6.4 *Mediolateral stability*. An adaptation of the “margin of stability” (MOS) introduced
9 by Hoff et al. (Hof et al., 2005) was used to quantify mediolateral dynamic stability at foot-
10 contact. The MOS corresponded to the difference between the mediolateral boundary of the
11 base of support ($BOS_{y_{max}}$) and the mediolateral position of the “extrapolated COM” at swing
12 foot-contact ($YCOM_{FC}$). Thus:

$$13 \quad MOS = BOS_{y_{max}} - YCOM_{FC}$$

14 $BOS_{y_{max}}$ was estimated with the mediolateral COP position at the time of rear foot-off
15 (Caderby et al., 2017; Yiou et al., 2016b). The mediolateral position of the extrapolated COM
16 at foot-contact ($yCOM_{FC}$) was calculated as follows:

$$17 \quad yCOM_{FC} = yM_{FC} + \frac{y'M_{FC}}{\omega_0}$$

18 where yM_{FC} and $y'M_{FC}$ are respectively the mediolateral COM position and velocity at foot-
19 contact, and ω_0 is the eigenfrequency of the body, modeled as an inverted pendulum and
20 calculated as follows:

$$21 \quad \omega_0 = \sqrt{\frac{g}{l}}$$

22 where $g=9.81 \text{ m/s}^2$ is the gravitational acceleration and l is the length of the inverted
23 pendulum, which in this study corresponded to 57.5% of body height (Winter et al., 1990).

24 Mediolateral dynamic stability at foot-contact is preserved on the condition that $yCOM_{FC}$ is

1 within BOSymax, which corresponds to a positive MOS. A negative MOS indicates a
2 mediolateral instability and implies that a corrective action is required to maintain balance.

3
4 2.6.5 *Vertical COM braking*. The “braking index” introduced by Do and colleagues (e.g.
5 (Chastan et al., 2009)) provides evidence that the central nervous system prepares for foot-
6 contact by decreasing the COM vertical velocity to achieve a soft landing (Honeine et al.,
7 2014, 2013). It was calculated as:

$$8 \quad \text{Braking index} = \frac{(V_{min} - V_{FC})}{V_{min}}$$

9
10 where V_{min} is the minimal vertical COM velocity and V_{FC} is the vertical COM velocity at
11 foot-contact.

12 13 2.7 Statistics

14 Mean values and standard deviations were calculated for each dependent variable. For ankle
15 dorsiflexion, a repeated-measures ANOVA model with one within-subject factor and one
16 between-subject factor was used. The within-subject factor was the time of the treatment (or
17 “time” factor; 2 levels: pre-treatment, post-treatment) and the between-subject factor was the
18 group (2 levels: sham, intervention). Additionally, a simple t-test was used to compare ankle
19 dorsiflexion between PD patients and healthy participants in the pre-treatment condition. For
20 GI parameters, a repeated-measures ANOVA model was also used. The within-subject factor
21 was the time (2 levels: pre-treatment, post-treatment) and the between-subject factor was the
22 group (3 levels: control, sham, intervention). The Tukey *post hoc* test was used when
23 required. The threshold of significance was set at $P < 0.05$. The Cohen’s *d* was used to assess
24 the effect sizes when repeated-measures ANOVA showed a significant time X group

1 interaction. The effect sizes were classified as trivial (<0.2), small (0.2-0.49), medium (0.5-
2 0.79), and large (≥ 0.8).

3

4 **3. Results**

5

6 3.1 Biomechanical Traces

7 The time course of the biomechanical traces was globally similar in the different groups and
8 time conditions. The traces obtained in a representative patient of the intervention group are
9 reported in figure 2.

10

11 [figure 2]

12

13 3.2 Ankle ROM

14

15 There was a significant effect of time ($F(1,17)=8.54, P<0.05$) and a significant time X group
16 interaction ($F(1,17)=8.54, P<0.05$) on the ankle dorsiflexion ROM. *Post hoc* analysis revealed
17 that it was significantly larger in the post-treatment than in the pre-treatment condition for the
18 intervention group only ($P<0.01, d=0.97$). In the pre-treatment condition, PD patients had a
19 significantly lower ankle ROM compared to healthy participants ($P<0.05, d=0.74$).

20

21 3.3 Initial posture and APA

22 There was no significant effect of time and group, nor any significant time X group
23 interaction on the following variables: initial COM position, APA duration, anteroposterior
24 peak COP displacement and mediolateral COM velocity at heel-off. In contrast, there was a
25 significant effect of time ($F(2,26)=15.28, P<0.001$) and a significant time X group interaction

1 (F(2,26)=5.64, $P<0.01$) on the anteroposterior COM velocity at heel-off. *Post hoc* analysis
2 revealed that it was significantly larger in the post-treatment than in the pre-treatment
3 condition for the intervention group only ($P<0.001$, $d=1.17$, Figure 3). *Post hoc* analysis
4 further showed that it was significantly larger for the intervention group in the post-treatment
5 condition than for the control group in both the pre- and post-treatment conditions ($P<0.05$,
6 $d=1.27$ and $d=1.33$, respectively). Finally, there was a significant effect of group on the
7 mediolateral peak of COP displacement (F(2,26)=4.62, $P<0.05$), with a larger value obtained
8 for the control than for both PD groups.

9

10 [figure 3]

11

12 3.4 Motor performance

13 There was no significant effect of group on the anteroposterior COM velocity at foot-contact,
14 but a significant effect of time (F(1,26)=19.58, $P<0.001$) and a significant time X group
15 interaction (F(2,26)=5.40, $P<0.05$). This interaction could be ascribed to a significantly larger
16 COM velocity in the post-treatment than in the pre-treatment condition for the intervention
17 ($P<0.01$) and the sham group ($P<0.05$, $d=0.78$ and $d=0.59$, respectively; Figure 4). Similarly,
18 there was no significant effect of group on the mean progression velocity, but a significant
19 effect of time (F(1,26)=14.05, $P<0.001$) and a significant time X group interaction
20 (F(2,26)=4.03, $P<0.05$). This variable was significantly larger in the post-treatment than in the
21 pre-treatment condition for the intervention group only ($P<0.01$, $d=1.07$). There was also a
22 significant effect of time (F(1,26)=8.00, $P<0.05$) and a time X group interaction
23 (F(2,26)=5.01, $P<0.05$) on the execution phase duration. The interaction could be ascribed to
24 a significantly lower execution phase duration in the post-treatment than in the pre-treatment

1 condition for the intervention group only ($P<0.01$, $d=1.27$). Finally, there was no significant
2 effect of time, group nor any time X group interaction on step length.

3

4 [figure 4]

5

6 3.5 Mediolateral stability and vertical COM braking

7 There was a significant effect of group on the mediolateral COM position at foot-contact
8 ($F(2,26)=30.10$, $P<0.001$) and the MOS ($F(2,26)=13.78$, $P<0.001$), but no significant effect of
9 time nor time X group interaction on these variables. The COM position at foot-contact was
10 larger for the control than for both PD groups, indicating that the COM fall towards the swing
11 leg during the execution phase was smaller for the control group. This resulted in a larger
12 MOS for the control group than for both PD groups (Figure 5). Finally, there was no
13 significant effect of time, group nor any significant time X group interaction on step width,
14 mediolateral COM velocity at foot-contact and vertical COM braking.

15

16 [figure 5]

17

18 4. Discussion

19

20 Impaired joint mobility is known to occur with normal ageing (Vandervoort et al., 1992) and
21 is exacerbated in PD patients (Halliday et al., 1998). Previous reports showed that short-term
22 *TS* stretching is an efficient training method to increase the ankle mobility in both young
23 adults and healthy elderly (Nakamura et al., 2017). Results of the present study show that it is
24 also efficient to improve ankle mobility in PD patients. The increase reached 44%.

25

1 Results further showed that several components of dynamical postural control were improved
2 following *TS* stretching. Specifically, the anteroposterior COM velocity at heel-off was
3 increased in the intervention group only, and this increase reached 32%. Previous reports
4 showed that larger anteroposterior COM velocity at heel-off can be reached at the expense of
5 a lengthened APA duration (Brenière et al., 1987). However, in the present experiment, APA
6 duration remained unchanged between the pre- and post-treatment conditions. PD patients in
7 the intervention group were therefore able to develop a larger quantity of initial forward
8 propulsive forces during an equivalent time, which indicates that their capacity to generate
9 forward APA was enhanced following the stretching. The improvement of motor performance
10 reported in this group (in terms of increased mean progression velocity, increased COM
11 velocity at foot-contact and reduced execution phase duration) can be seen as a consequence
12 of this enhanced capacity to generate APA (Brenière et al., 1987).

13

14 Now, results further showed that, in contrast to all the other GI variables, the anteroposterior
15 COM velocity at foot-contact was also increased in the sham group following the treatment.
16 This finding suggests that part of the increase in this variable observed in the intervention
17 group could probably be assigned to a placebo effect. Such confounding effect was expected
18 since it is known that PD patients are particularly influenced by the belief of improvement
19 (Lidstone et al., 2010). However, this placebo effect only concerned the COM velocity at the
20 time of foot-contact, and this increase was smaller in the sham than in the intervention group
21 (12% vs. 8%), and so the effect size (0.78 vs. 0.59). The improvement in the postural
22 organization of GI following *TS* stretching can therefore be considered as consistent.

23

24 Interestingly, PD patients who were exposed to the *TS* stretching reached an even larger
25 anteroposterior COM velocity at heel-off than participants within the control group (healthy

1 older adults). This finding can be ascribed to the relatively low-level of motor impairment of
2 the PD patients included in the present study. All were able to walk without assistance, did
3 not experience freezing, and had relatively low motor disorders according to the MDS-
4 UPDRS and Hoehn & Yahr scale (cf. table 1). Their locomotor function was therefore not
5 much different from the healthy age-matched participants, as could also be reflected in the
6 equivalent anteroposterior APA spatiotemporal parameters in the pre-treatment condition. As
7 a consequence, increasing the initial COM velocity in these patients resulted in a significant
8 difference with the control group in the post-treatment condition.

9

10 In fact, the effects of PD on the postural organization of GI only manifested as changes in the
11 mediolateral stability-related parameters. Specifically, the amplitude of the mediolateral APA
12 was lower in PD patients than in healthy participants. Previous study in healthy participants
13 showed that the amplitude of these APA was predictive of the MOS value at foot-contact
14 (Yiou et al., 2016a). In the present study, the lower MOS value in the PD patients could
15 therefore be ascribed to a lower capacity of PD patients to generate mediolateral APA.

16

17 Our findings regarding the effect of PD on APA are in accordance with Mancini et al. (2009)
18 who reported that, in early and untreated PD patients, the mediolateral component of the COP
19 displacement during APA was altered, but not its anteroposterior component. Hypometric
20 mediolateral APA may lead to an excessive weight shift toward the swing leg during the first
21 step, as observed in PD by some authors (Okada et al., 2011a, 2011b), which increases the
22 risk of imbalance in the frontal plane (Yiou et al., 2016a). Mancini et al. (2009) suggested that
23 the pathology of PD may have a specific effect on loading/unloading of the legs early in the
24 disease, consistent with abnormal mediolateral, but not anteroposterior, sway during quiet
25 stance in PD patients (Mitchell et al., 1995). However, this assumption contrasts with the

1 study of Carpinella et al. (2007) which reported a reduced backward COP displacement in
2 early PD patients (phases 1 and 2 of Hoehn and Yahr scale). Differences in the initial posture
3 and/or inclusion criteria may have explained this discrepancy (Mancini et al. 2009). For
4 example, inclusion criteria for PD subjects were different, since all subjects in the study of
5 Mancini et al. (2009) were untreated, whereas several subjects in the Carpinella's study were
6 tested on dopaminergic medication. Despite this contradiction in early stage, it seems
7 admitted that later in the disease, the magnitude of both mediolateral and anteroposterior APA
8 becomes bradykinetic in PD (Halliday et al., 1998).

9
10 Similar to the anteroposterior APA, results of the present study showed that the capacity to
11 actively brake the COM fall during GI was unaltered in PD patients. This finding contrasts
12 with the study of Chastan et al. (2009) which reported that this capacity was altered in
13 advanced PD patients. Once again, a difference in the PD clinical stage may probably explain
14 this discrepancy. Globally, these findings suggest that, in PD patients, the progressive decline
15 in the control of mediolateral stability, vertical COM braking and forward propulsive forces
16 may not follow the same evolution, maybe due to distinct systems within the basal ganglia
17 circuitry. Short-term *TS* stretching did not improve the control of mediolateral stability, nor
18 the capacity to brake the vertical COM fall. *It is not excluded that more advanced PD patients*
19 *than in our study, with more severe muscle rigidity, may beneficiate from *TS* stretching to*
20 *improve these two parameters.*

21
22 *The present study has several limitations: 1) the PD patients involved in the experiment had*
23 *relatively low-level of motor impairment. It is not known whether short-term stretching may*
24 *also be beneficial to PD patients with more severe symptoms; 2) the sample sizes were small.*
25 *We were however confident on the reliability of our results because of the large size effects*

1 found for most variables and the biomechanical coherence of data; 3) only short-term
2 stretching effects were considered. To what extent PD patient might benefit from long-
3 term stretching is unknown; 4) the carry-over effects were not evaluated.

4

5 In conclusion, the present results showed that short-term *TS* stretching substantially improved
6 ankle mobility in PD patients. The capacity to generate forward propulsive forces during APA
7 was also increased, with consequent improvement in motor performance. Now, it is obvious
8 that PD motor impairment goes far beyond a simple alteration in ankle mobility. *However,*
9 *our results suggest that TS stretching might beneficially be integrated in multicomponent*
10 *exercise programs, e.g. including strength, balance and gait, mental training (Shen et al.,*
11 *2016), or video game-based exercise program (Maillot et al., 2014) to further improve*
12 *postural control in PD patients.*

13

14 **Conflict of interest statement:** none

15 **Funding:** this work was funded by the Ministry of Higher Education, Research and
16 Innovation

17 **Author contributions:** TV, AD, IM, GL, SM, PF and EY contributed to project creation,
18 data collection, data analysis, drafted the manuscript, discussed the results, and participated in
19 the revision of the manuscript.

20

21 **References**

- 22 Bazalgette, D., Zattara, M., Bathien, N., Bouisset, S., Rondot, P., 1987. Postural adjustments
23 associated with rapid voluntary arm movements in patients with Parkinson's disease. *Adv*
24 *Neurol* 45, 371–374.
- 25 Bonora, G., Mancini, M., Carpinella, I., Chiari, L., Horak, F.B., Ferrarin, M., 2017. Gait
26 initiation is impaired in subjects with Parkinson's disease in the OFF state: Evidence from the
27 analysis of the anticipatory postural adjustments through wearable inertial sensors. *Gait*
28 *Posture* 51, 218–221. <https://doi.org/10.1016/j.gaitpost.2016.10.017>
- 29 Bouisset, S., Do, M.-C., 2008. Posture, dynamic stability, and voluntary movement.
30 *Neurophysiologie Clinique/Clinical Neurophysiology* 38, 345–362.
31 <https://doi.org/10.1016/j.neucli.2008.10.001>

1 Brenière, Y., Do, M.-C., 1986. When and how does steady state gait movement induced from
2 upright posture begin? *J Biomech* 19, 1035–1040. [https://doi.org/10.1016/0021-](https://doi.org/10.1016/0021-9290(86)90120-x)
3 [9290\(86\)90120-x](https://doi.org/10.1016/0021-9290(86)90120-x)

4 Brenière, Y., Do, M.-C., Bouisset, S., 1987. Are dynamic phenomena prior to stepping
5 essential to walking? *J Mot Behav* 19, 62–76.
6 <https://doi.org/10.1080/00222895.1987.10735400>

7 Caderby, T., Yiou, E., Peyrot, N., Bonazzi, B., Dalleau, G., 2013. Detection of swing heel-off
8 event in gait initiation using force-plate data. *Gait Posture* 37, 463–466.
9 <https://doi.org/10.1016/j.gaitpost.2012.08.011>

10 Caderby, T., Yiou, E., Peyrot, N., de Viviés, X., Bonazzi, B., Dalleau, G., 2017. Effects of
11 Changing Body Weight Distribution on Mediolateral Stability Control during Gait Initiation.
12 *Front Hum Neurosci* 11, 127. <https://doi.org/10.3389/fnhum.2017.00127>

13 Carlsöö, S., 1966. The initiation of walking. *Acta Anat (Basel)* 65, 1–9.

14 Carpinella, I., Crenna, P., Calabrese, E., Rabuffetti, M., Mazzoleni, P., Nemni, R., Ferrarin,
15 M., 2007. Locomotor function in the early stage of Parkinson’s disease. *IEEE Trans Neural*
16 *Syst Rehabil Eng* 15, 543–551. <https://doi.org/10.1109/TNSRE.2007.908933>

17 Chastan, N., Do, M.-C., Bonneville, F., Torny, F., Bloch, F., Westby, G.W.M., Dormont, D.,
18 Agid, Y., Welter, M.-L., 2009. Gait and balance disorders in Parkinson’s disease: impaired
19 active braking of the fall of centre of gravity. *Mov. Disord.* 24, 188–195.
20 <https://doi.org/10.1002/mds.22269>

21 Crenna, P., Frigo, C., 1991. A motor programme for the initiation of forward-oriented
22 movements in humans. *J. Physiol. (Lond.)* 437, 635–653.
23 <https://doi.org/10.1113/jphysiol.1991.sp018616>

24 Delafontaine, A., Fourcade, P., Honeine, J.L., Ditcharles, S., Yiou, E., 2018. Postural
25 adaptations to unilateral knee joint hypomobility induced by orthosis wear during gait
26 initiation. *Sci Rep* 8, 830. <https://doi.org/10.1038/s41598-018-19151-1>

27 Delafontaine, A., Gagey, O., Colnaghi, S., Do, M.-C., Honeine, J.-L., 2017. Rigid Ankle Foot
28 Orthosis Deteriorates Mediolateral Balance Control and Vertical Braking during Gait
29 Initiation. *Front Hum Neurosci* 11, 214. <https://doi.org/10.3389/fnhum.2017.00214>

30 Delafontaine, A., Honeine, J.-L., Do, M.-C., Gagey, O., Chong, R.K., 2015. Comparative gait
31 initiation kinematics between simulated unilateral and bilateral ankle hypomobility: Does
32 bilateral constraint improve speed performance? *Neurosci. Lett.* 603, 55–59.
33 <https://doi.org/10.1016/j.neulet.2015.07.016>

34 Gajdosik, R.L., Vander Linden, D.W., McNair, P.J., Williams, A.K., Riggin, T.J., 2005.
35 Effects of an eight-week stretching program on the passive-elastic properties and function of
36 the calf muscles of older women. *Clinical Biomechanics* 20, 973–983.
37 <https://doi.org/10.1016/j.clinbiomech.2005.05.011>

38 Halliday, S.E., Winter, D.A., Frank, J.S., Patla, A.E., Prince, F., 1998. The initiation of gait in
39 young, elderly, and Parkinson’s disease subjects. *Gait Posture* 8, 8–14.
40 [https://doi.org/10.1016/s0966-6362\(98\)00020-4](https://doi.org/10.1016/s0966-6362(98)00020-4)

41 Hof, A.L., Gazendam, M.G.J., Sinke, W.E., 2005. The condition for dynamic stability. *J*
42 *Biomech* 38, 1–8. <https://doi.org/10.1016/j.jbiomech.2004.03.025>

43 Honeine, J.-L., Schieppati, M., Crisafulli, O., Do, M.-C., 2016. The Neuro-Mechanical
44 Processes That Underlie Goal-Directed Medio-Lateral APA during Gait Initiation. *Front Hum*
45 *Neurosci* 10. <https://doi.org/10.3389/fnhum.2016.00445>

46 Honeine, J.-L., Schieppati, M., Gagey, O., Do, M.-C., 2014. By counteracting gravity, triceps
47 surae sets both kinematics and kinetics of gait. *Physiol Rep* 2, e00229.
48 <https://doi.org/10.1002/phy2.229>

49 Honeine, J.-L., Schieppati, M., Gagey, O., Do, M.-C., 2013. The Functional Role of the
50 Triceps Surae Muscle during Human Locomotion. *PLoS One* 8.

1 <https://doi.org/10.1371/journal.pone.0052943>
2 Konor, M.M., Morton, S., Eckerson, J.M., Grindstaff, T.L., 2012. Reliability of three
3 measures of ankle dorsiflexion range of motion. *Int J Sports Phys Ther* 7, 279–287.
4 Lepers, R., Brenière, Y., 1995. The role of anticipatory postural adjustments and gravity in
5 gait initiation. *Exp Brain Res* 107, 118–124. <https://doi.org/10.1007/bf00228023>
6 Lidstone, S.C., Schulzer, M., Dinelle, K., Mak, E., Sossi, V., Ruth, T.J., de la Fuente-
7 Fernández, R., Phillips, A.G., Stoessl, A.J., 2010. Effects of Expectation on Placebo-Induced
8 Dopamine Release in Parkinson Disease. *Archives of General Psychiatry* 67, 857.
9 <https://doi.org/10.1001/archgenpsychiatry.2010.88>
10 Mancini, M., Nutt, J.G., Horak, F.B., 2020. Chapter 8 - Is freezing of gait a balance disorder?,
11 in: Mancini, M., Nutt, J.G., Horak, F.B. (Eds.), *Balance Dysfunction in Parkinson's Disease*.
12 Academic Press, pp. 139–161. <https://doi.org/10.1016/B978-0-12-813874-8.00008-8>
13 Mancini, M., Zampieri, C., Carlson-Kuhta, P., Chiari, L., Horak, F.B., 2009. Anticipatory
14 postural adjustments prior to step initiation are hypometric in untreated parkinson's disease:
15 an accelerometer-based approach. *Eur J Neurol* 16, 1028–1034.
16 <https://doi.org/10.1111/j.1468-1331.2009.02641.x>
17 Martin, R.L., McPoil, T.G., 2005. Reliability of ankle goniometric measurements: a literature
18 review. *J Am Podiatr Med Assoc* 95, 564–572. <https://doi.org/10.7547/0950564>
19 Mitchell, S.L., Collins, J.J., De Luca, C.J., Burrows, A., Lipsitz, L.A., 1995. Open-loop and
20 closed-loop postural control mechanisms in Parkinson's disease: increased mediolateral
21 activity during quiet standing. *Neurosci. Lett.* 197, 133–136. [https://doi.org/10.1016/0304-](https://doi.org/10.1016/0304-3940(95)11924-1)
22 [3940\(95\)11924-1](https://doi.org/10.1016/0304-3940(95)11924-1)
23 Nakamura, M., Ikezoe, T., Nishishita, S., Umehara, J., Kimura, M., Ichihashi, N., 2017. Acute
24 effects of static stretching on the shear elastic moduli of the medial and lateral gastrocnemius
25 muscles in young and elderly women. *Musculoskelet Sci Pract* 32, 98–103.
26 <https://doi.org/10.1016/j.msksp.2017.09.006>
27 Okada, Y., Fukumoto, T., Takatori, K., Nagino, K., Hiraoka, K., 2011a. Abnormalities of the
28 First Three Steps of Gait Initiation in Patients with Parkinson's Disease with Freezing of Gait.
29 *Parkinson's disease* 2011, 202937. <https://doi.org/10.4061/2011/202937>
30 Okada, Y., Fukumoto, T., Takatori, K., Nagino, K., Hiraoka, K., 2011b. Variable initial swing
31 side and prolonged double limb support represent abnormalities of the first three steps of gait
32 initiation in patients with Parkinson's disease with freezing of gait. *Front Neurol* 2, 85.
33 <https://doi.org/10.3389/fneur.2011.00085>
34 Postuma, R.B., Berg, D., Stern, M., Poewe, W., Olanow, C.W., Oertel, W., Obeso, J., Marek,
35 K., Litvan, I., Lang, A.E., Halliday, G., Goetz, C.G., Gasser, T., Dubois, B., Chan, P., Bloem,
36 B.R., Adler, C.H., Deuschl, G., 2015. MDS clinical diagnostic criteria for Parkinson's
37 disease. *Mov. Disord.* 30, 1591–1601. <https://doi.org/10.1002/mds.26424>
38 Raza, C., Anjum, R., Shakeel, N. ul A., 2019. Parkinson's disease: Mechanisms, translational
39 models and management strategies. *Life Sciences* 226, 77–90.
40 <https://doi.org/10.1016/j.lfs.2019.03.057>
41 Shrier, I., Gossal, K., 2000. Myths and Truths of Stretching: Individualized
42 Recommendations for Healthy Muscles. *The Physician and Sportsmedicine* 28, 57–63.
43 <https://doi.org/10.3810/psm.2000.08.1159>
44 Vandervoort, A.A., Chesworth, B.M., Cunningham, D.A., Paterson, D.H., Rechnitzer, P.A.,
45 Koval, J.J., 1992. Age and sex effects on mobility of the human ankle. *J Gerontol* 47, M17-
46 21. <https://doi.org/10.1093/geronj/47.1.m17>
47 Webber, S.C., Porter, M.M., 2010. Reliability of Ankle Isometric, Isotonic, and Isokinetic
48 Strength and Power Testing in Older Women. *Physical Therapy* 90, 1165–1175.
49 <https://doi.org/10.2522/ptj.20090394>
50 Winter, D.A., 1995. A.B.C. (anatomy, biomechanics and control) of balance during standing

1 and walking. Waterloo Biomechanics, Waterloo, Ont.
2 Winter, D.A., Patla, A.E., Frank, J.S., 1990. Assessment of balance control in humans. *Med*
3 *Prog Technol* 16, 31–51.
4 Yiou, E., Artico, R., Teyssedre, C.A., Labaune, O., Fourcade, P., 2016a. Anticipatory Postural
5 Control of Stability during Gait Initiation Over Obstacles of Different Height and Distance
6 Made Under Reaction-Time and Self-Initiated Instructions. *Front Hum Neurosci* 10.
7 <https://doi.org/10.3389/fnhum.2016.00449>
8 Yiou, E., Caderby, T., Delafontaine, A., Fourcade, P., Honeine, J.-L., 2017. Balance control
9 during gait initiation: State-of-the-art and research perspectives. *World J Orthop* 8, 815–828.
10 <https://doi.org/10.5312/wjo.v8.i11.815>
11 Yiou, E., Teyssède, C., Artico, R., Fourcade, P., 2016b. Comparison of base of support size
12 during gait initiation using force-plate and motion-capture system: A Bland and Altman
13 analysis. *J Biomech* 49, 4168–4172. <https://doi.org/10.1016/j.jbiomech.2016.11.008>
14

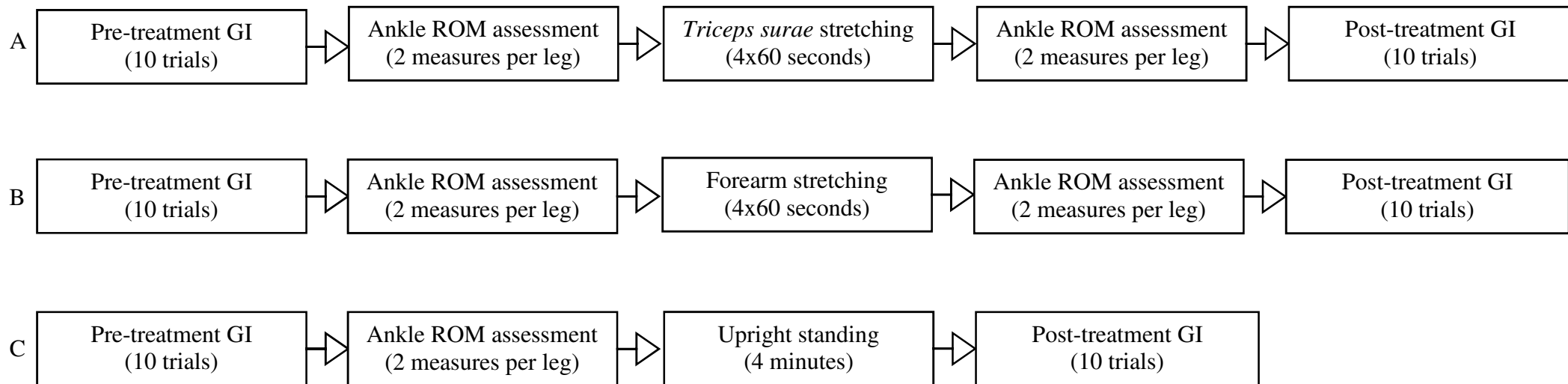


Figure 2

Intervention group

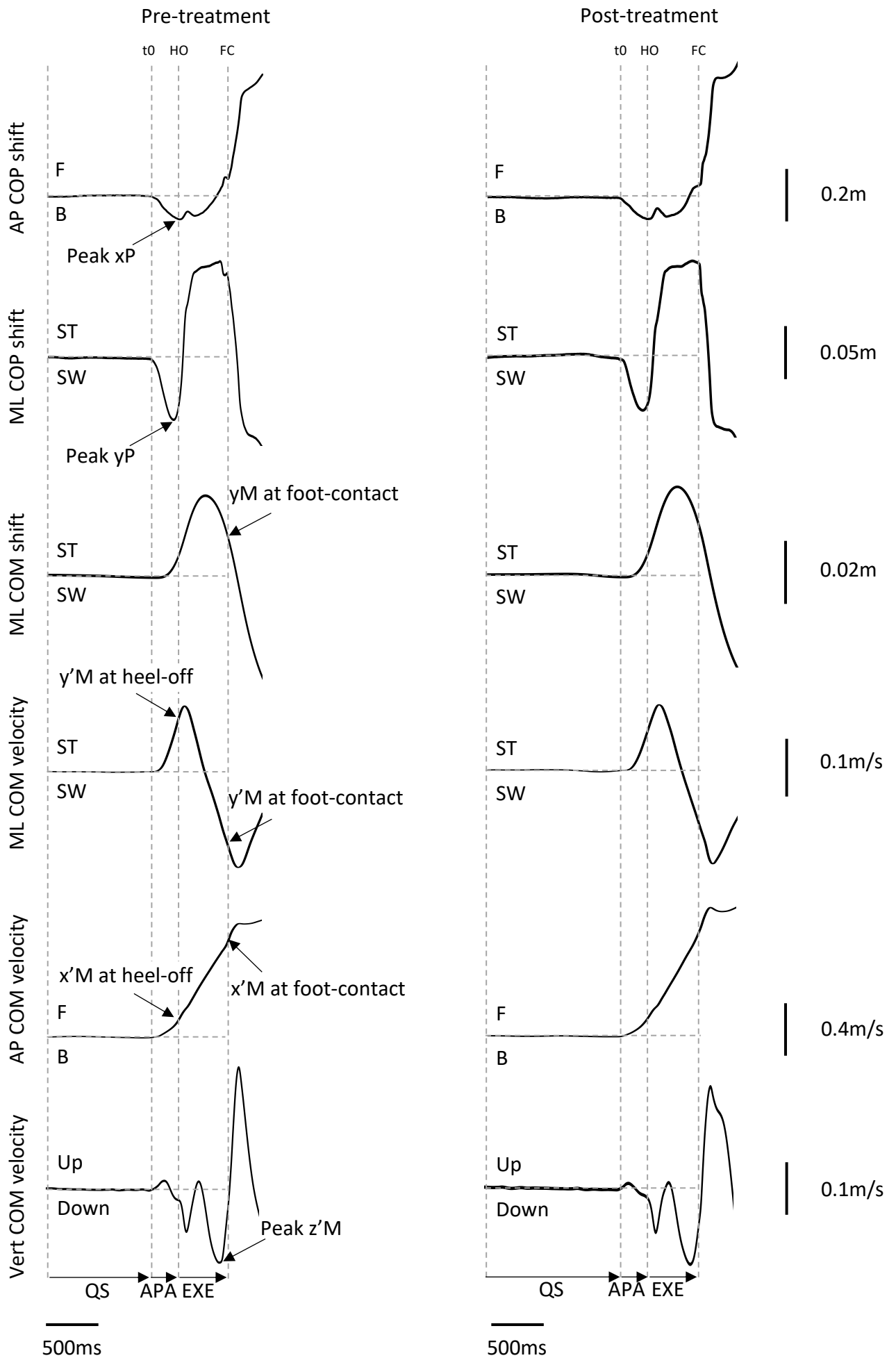


Figure 3

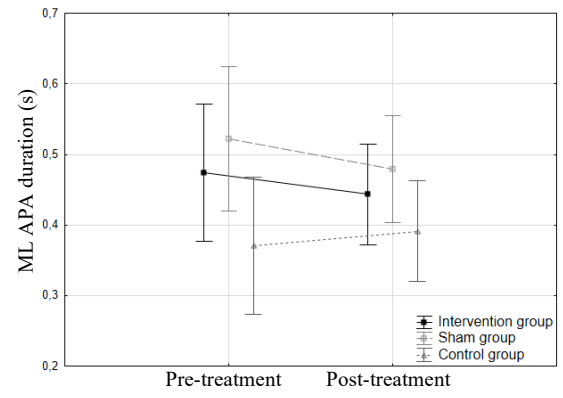
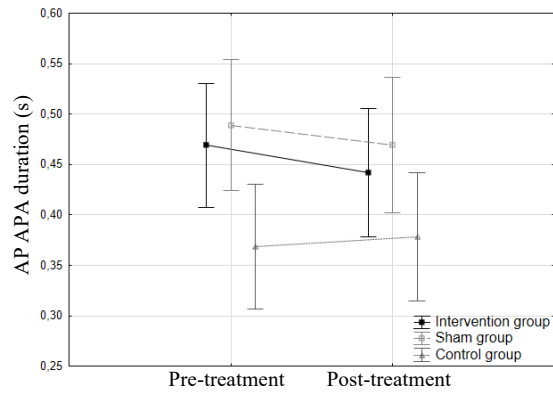
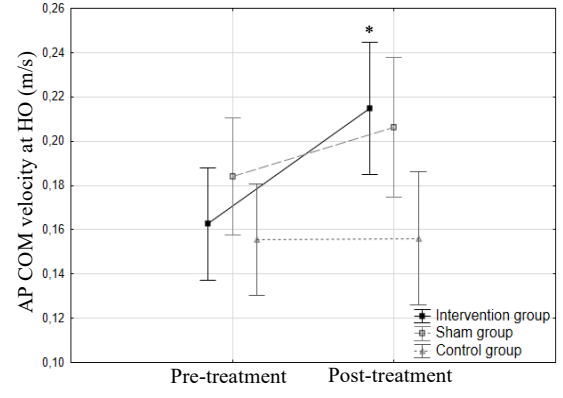
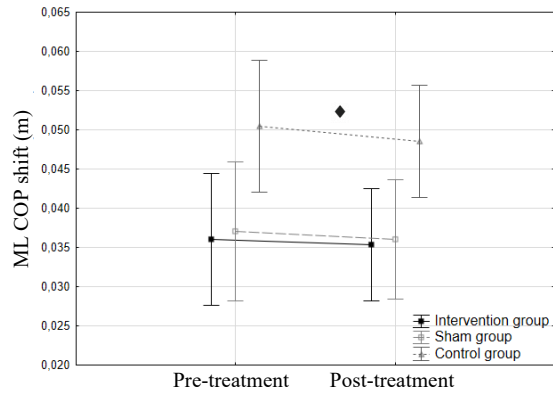


Figure 4

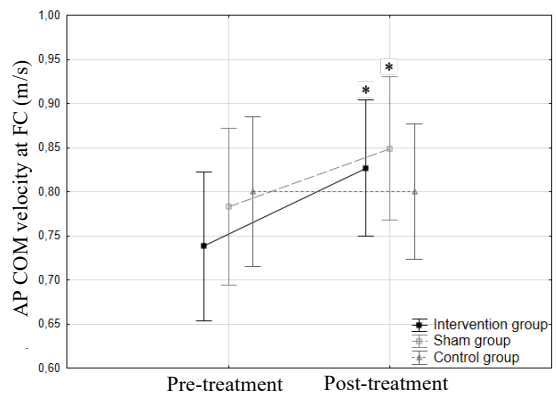
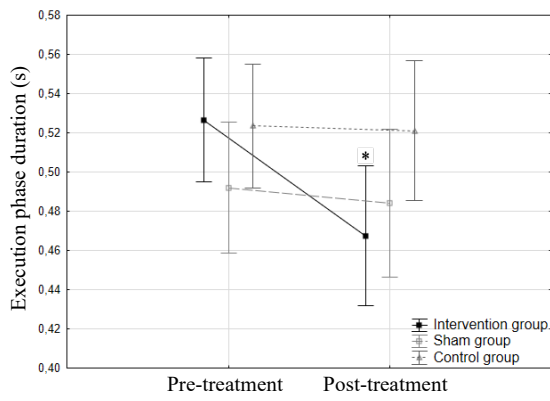
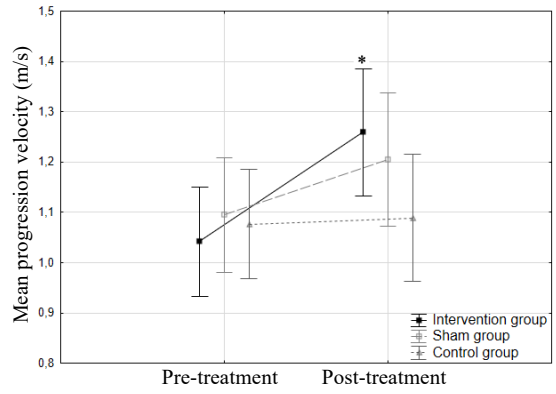
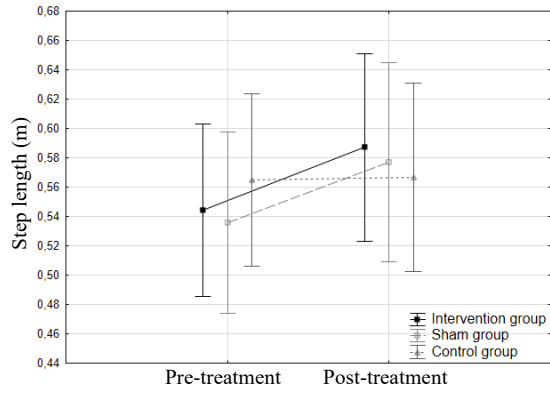
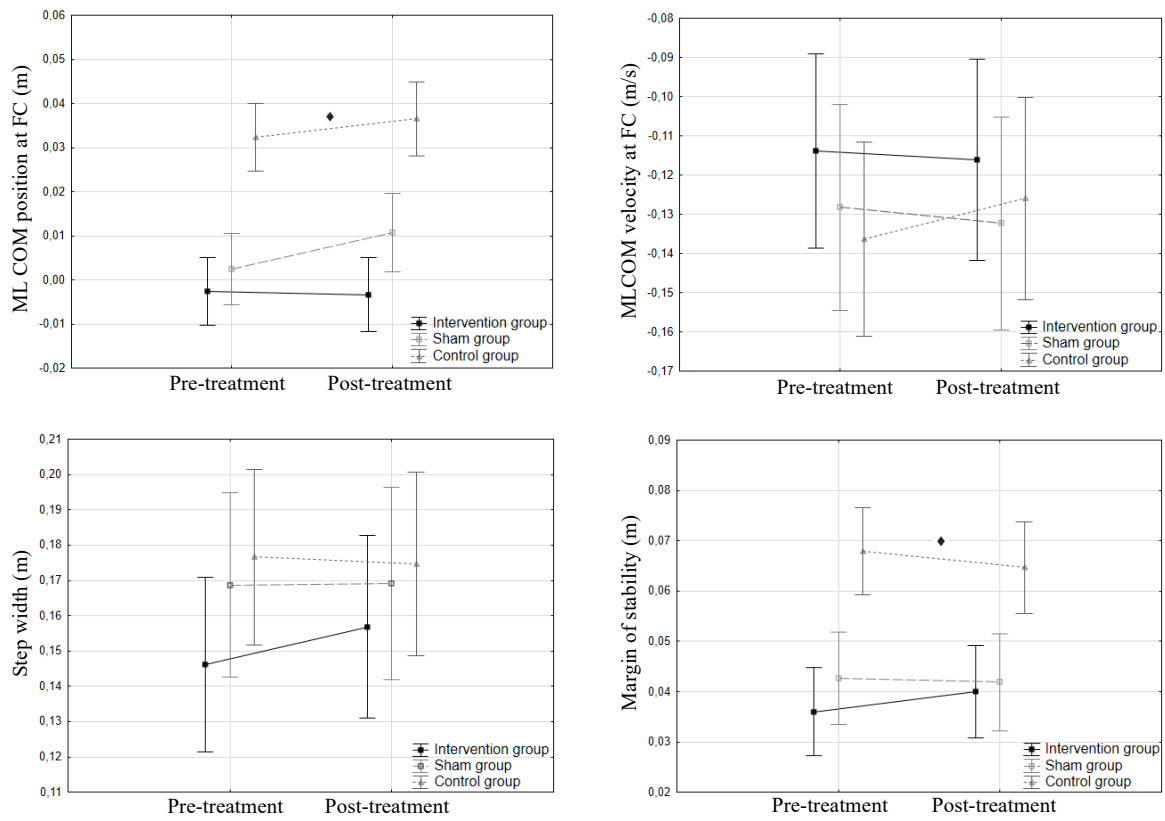


Figure 5



| | Subjects | Genre | Age (years) | Height (meters) | Body mass (kilograms) | Disease Durations (years) | Most disabled side | Hoehn and Yahr state | MDS-UPDRS (part 3) |
|--------------------|----------|-------|--------------|-----------------|-----------------------|---------------------------|--------------------|----------------------|--------------------|
| Intervention group | 1 | M | 77 | 1.58 | 62 | 2 | R | 2 | 18 |
| | 2 | F | 70 | 1.74 | 70 | 8 | L | 3 | 28 |
| | 3 | M | 76 | 1.70 | 62 | 5 | R | 2 | 14 |
| | 4 | F | 63 | 1.69 | 76 | 7 | R | 2 | 10 |
| | 5 | M | 71 | 1.70 | 76 | 13 | L | 2 | 16 |
| | 6 | M | 67 | 1.70 | 70 | 6 | L | 2 | 14 |
| | 7 | M | 66 | 1.58 | 45 | 5 | L | 2 | 36 |
| | 8 | F | 77 | 1.73 | 82 | 5 | R | 2 | 14 |
| | 9 | F | 69 | 1.76 | 87 | 2 | R | 2 | 35 |
| | 10 | M | 57 | 1.60 | 66 | 9 | L | 2 | 26 |
| Mean (SD) | - | - | 69.30 (6.45) | 1.68 (0.07) | 69.60 (11.89) | 6.20 (3.29) | - | 2.10 (0.32) | 21.10 (9.41) |
| Sham group | 1 | M | 68 | 1.60 | 52 | 4 | R | 2 | 17 |
| | 2 | M | 57 | 1.55 | 48 | 2 | L | 2 | 35 |
| | 3 | M | 63 | 1.57 | 40 | 4 | L | 2 | 21 |
| | 4 | F | 71 | 1.80 | 90 | 6 | R | 3 | 50 |
| | 5 | M | 69 | 1.70 | 82 | 2 | L | 2 | 32 |
| | 6 | M | 74 | 1.59 | 51 | 12 | R | 3 | 20 |
| | 7 | F | 70 | 1.75 | 74 | 8 | L | 2 | 20 |
| | 8 | F | 56 | 1.78 | 90 | 3 | L | 2 | 43 |
| | 9 | F | 74 | 1.65 | 65 | 14 | L | 2 | 36 |
| Mean (SD) | - | - | 66.89 (6.75) | 1.67 (0.10) | 65.78 (19.02) | 6.11 (4.37) | - | 2.22 (0.44) | 30.44 (11.63) |
| Control group | 1 | F | 70 | 1.71 | 52 | | | | |
| | 2 | F | 78 | 1.55 | 65 | | | | |
| | 3 | F | 69 | 1.64 | 55 | | | | |
| | 4 | M | 79 | 1.78 | 67 | | | | |
| | 5 | F | 67 | 1.60 | 86 | | | | |
| | 6 | F | 65 | 1.62 | 71 | - | - | - | - |
| | 7 | F | 74 | 1.60 | 54 | | | | |
| | 8 | F | 76 | 1.62 | 56 | | | | |
| | 9 | F | 69 | 1.75 | 68 | | | | |
| | 10 | M | 69 | 1.78 | 74 | | | | |
| Mean (SD) | - | - | 71.10 (4.56) | 1.67 (8.30) | 64.90 (10.86) | - | - | - | - |