Experimental Brain Research (2018) 236:963–972
https://doi.org/10.1007/s00221-018-5189-3

RESEARCH ARTICLE

Influence of dual-task constraints on the interaction between posture and movement during a lower limb pointing task

Marcelo Guimarães Silva[1,2,3] · **Lucas Struber**[3] · **José Geraldo T. Brandão**[2] · **Olivier Daniel**[3] · **Vincent Nougier**[3]

Received: 31 May 2017 / Accepted: 24 January 2018 / Published online: 30 January 2018

Abstract

One of the challenges regarding human motor control is making the movement fluid and at a limited cognitive cost. The coordination between posture and movement is a necessary requirement to perform daily life tasks. The present experiment investigated this interaction in 20 adult men, aged 18–30 years. The cognitive costs associated to postural and movement control when kicking towards a target was estimated using a dual-task paradigm (secondary auditory task). Results showed that addition of the attentional demanding cognitive task yielded a decreased kicking accuracy and an increased timing to perform the movement, mainly during the backswing motion. In addition, significant differences between conditions were found for COP and COM displacement (increased amplitude, mean speed) on the anteroposterior axis. However, no significant differences between conditions were found on the mediolateral axis. Finally, EMG analysis showed that dual-task condition modified the way anticipatory postural adjustments (APAs) were generated. More specifically, we observed an increase of the peroneus longus activity, whereas the temporal EMG showed a decrease of its latency with respect to movement onset. These results suggested a functional adaptation resulting in an invariance of overall APAs, emphasizing that cognitive, postural, and motor processes worked dependently.

Keywords Posture–movement interactions · Dual-task performance · Anticipatory postural adjustments

Introduction

One of the challenges regarding human motor control is executing movements as smooth as possible and at the lowest cognitive cost. Even though posture and movement are frequently investigated separately, their coordination is a necessary requirement to perform daily life tasks. Indeed, there is need for an accurate performance of goal-directed movements, on one hand, and for the maintenance of equilibrium with an appropriate posture or set of postures, on the other hand (Massion 1992; Bloem et al. 2001; Beilock et al. 2002).

Two modes of coordination between posture and movement have been identified (Massion 1992; Robert et al. 2007). In the "hierarchical" mode of coordination, the execution of voluntary movements is generally accompanied by postural adjustments, and in most cases, the muscles responsible for these postural adjustments are activated before those acting as prime movers (Robert et al. 2007). In the "parallel" mode of coordination (Massion 1992; Massion et al. 2004), postural adjustments and movement are controlled by parallel pathways. In this mode of coordination, postural changes often occur shortly before movement onset.

Studies dealing with feedforward aspects of motor control commonly used posture–movement coordination tasks requiring the generation of Anticipatory Postural Adjustments (APAs). APAs are supposed to facilitate the coordination between posture and movement to minimize the equilibrium disturbance associated with movement execution. More precisely, they are predictive processes of control mostly revealed by an increased activity of postural muscles prior to the onset of a focal movement, as

---

✉ Marcelo Guimarães Silva
marceloguimas@bol.com.br

[1] CAPES Foundation, Ministry of Education of Brazil, Brasilia, DF 70040-020, Brazil

[2] Laboratorio de Biomecânica, Departamento Mecânica, Campus Guaratinguetá, UNESP-Univ Estadual Paulista, Av. Dr. Ariberto Pereira da Cunha, 333, Guaratinguetá, SP CEP 12516-410, Brazil

[3] Univ. Grenoble Alpes, CNRS, CHU Grenoble Alpes, TIMC-IMAG, 38000 Grenoble, France

for example when raising a limb during the course of self-generated movements (Bouisset and Zattara 1987b; Monjo and Forestier 2014) as well as to contribute to the propulsion of the limb during a voluntary movement (Fourcade et al. 2014).

These APAs reflect a separate control process which may depend on the type and magnitude of the motor action, but which has also some degree of autonomy (Bouisset and Zattara 1987b; Robert et al. 2007). For instance, in lower limb movements, APAs depend on the initial and final postures (Monjo and Forestier 2014), and also on previous experience (Fourcade et al. 2014). However, it has been shown that while APAs are certainly generated prior to an intentional motor action, they are also produced to prepare for an external predictable perturbation.

Previous studies investigating the effects of dual tasks on movement accuracy showed that arm pointing movements towards a target located within or beyond reach and trunk movements were incorporated into the goal of pointing (Ma and Feldman 1995; Wang and Stelmach 1998; Archambault et al. 1999; Pozzo et al. 2002). Hand trajectory and kinematics remained fairly constant whether the trunk took part in the pointing movement.

Disturbances caused by a simultaneous secondary goal have been also explored during tasks involving lower limbs, in which posture was altered while kicking a ball as accurately as possible (Rios et al. 2015; Conceição et al. 2016). Results suggested that precision tasks are influenced by the required interactions with external stimuli as they may be the factor driving the pattern of attentional demand.

In addition, various authors (Lam et al. 2010; Hart et al. 2014) found that when learning a motor task such as golf or soccer, which goal was to deliver the ball as accurately as possible to the specified target, performance in the secondary task was worse during the movement preparation phase (prior to the initiation of the backswing) than during execution of the motor task (the forward swing of the putter or foot). Based upon these findings and those of similar studies (Chew-Bullock et al. 2012; Carr et al. 2013), the authors concluded that movement preparation requires greater attentional resources than does movement execution.

Besides, the attentional demand required by the coordination of posture and pointing movements depends on various factors such as the available sensory information, the nature and complexity of the postural and motor tasks, or subject's sensory-motor expertise or deficits (Woollacott and Shumway-Cook 2001).

Within this context, the purpose of the present experiment was to further investigate the postural and motor organization of the lower limbs when performing an accurate kicking task, with or without an additional cognitive load. To maintain a satisfying motor performance in the dual-task condition, we hypothesized a functional adaptation of the APAs.

Methods

Participants

Twenty healthy male participants from a recreational soccer team (mean age 22.1 years ± 3.11, body height 1.79 m ± 0.06, body mass 74.73 kg ± 8.41) participated in the experiment. Participants practiced three times a week and participated in about 15 games per season. This study was approved by the local ethics committee, and in conformity with the Helsinki Convention informed consent was obtained from all participants.

Task

Participants' task was to kick a ball with the inside of the right foot (motor limb), as accurately as possible, toward a target. The target (0.40 m × 0.40 m) with a smaller target inserted (0.10 m × 0.10 m) was set in front of participants, at a distance of 3.70 m and at the level of the ground. All participants declared previously the right foot as their preferable, dominant limb, to kick the ball. They were experienced in performing this task. As instructed, the kicking movement was executed at a comfortable speed and in a self-paced manner following an auditory signal, as a precision soccer passing.

The task was performed in two different conditions. In the single-task condition, participants performed the kick alone. In the dual-task condition, participants performed the primary kicking task together with an additional secondary cognitive task. For this cognitive task, participants wore an audio helmet and counted the number of "beep" occurring in a randomized sequence of "beep" and "bop" presented at a time interval of 1 s, for a total of 20 s. Participants initiated the movement when they wanted following an auditory signal delivered by the experimenter. They were instructed to keep a quiet upright stance for few seconds before each kicking. During dual-task condition, they performed only the cognitive task for few seconds before starting the kicking movement. However, performance in that cognitive task was not measured separately from the motor task. Once the kick was achieved, they returned to the starting position without stopping the movement. 16 kicks were performed in each condition for a total of 32 trials, by blocks of four trials (four blocks of trials per condition). The blocks of trials were randomized across participants. A time rest between each kick and each block was allowed, whenever necessary.

Data recording and analysis

Participants' left foot (postural limb) remained on a force platform (AMTI®, Accugait model), which was flush with the floor, throughout movement execution. The right foot was placed outside the force platform and parallel to the postural foot. The ball was placed next to the force platform. Force platform was used to analyze left center of foot pressure displacements (COP) and ground reaction forces (GRF). Force platform signals were sampled at 100 Hz (12 bits A/D converter) and then filtered with a second-order Butterworth filter (10 Hz low-pass cutoff frequency with dual pass to remove phase shift).

Electromyographic activity (EMG) of four postural muscles of the left limb was also recorded (surface EMG electrodes Delsys, Inc., Boston, Massachusetts; DE 2.1 single-differential, parallel-bar configuration, contact Material 99.9% Ag, contact Spacing 10 mm, with a detection area of 10 mm2). The EMG electrodes were placed on the biceps femoris (BF), rectus femoris (RF), medial gastrocnemius (GM), and peroneus longus (PL). Procedure for placing the electrodes followed the Surface Electromyography for the Non-Invasive Assessment of Muscles (SENIAM) (1999) recommendations. EMG signals were sampled at 2000 Hz, filtered with a fourth-order Butterworth filter (20–450 Hz band-pass) according to the manufacturer's recommendations, and then rectified full-wave.

To record kinematics data and estimate center of mass displacements (COM), an optoelectronic system (Codamotion®) was used at a sampling frequency of 100 Hz. We used an anthropometric model based on sixteen markers allowing computation of the position of the whole-body COM (Winter 1990). These markers were positioned at the following sites: Left and right ear, acromion, anterior superior iliac spine, knee, ankle, fifth metatarsal, elbow, and wrist joints.

Four cameras positioned in front of and on both sides of participants recorded the 3D coordinates expressed as a right-handed orthogonal reference frame fixed on the ground. The following sign convention was adopted: x for AP axis, horizontal and pointed to the center of the target (positive forward and negative backward); y for ML axis, perpendicular to x and z (positive to the right and negative to the left); z for craniocaudal axis (positive upward and negative downward). In the present study, we analyzed COM displacements on both AP and ML axes. Trials were viewed off-line on a monitor screen and temporally synchronized according to the first visible deflection of the right ankle kinematics signal, which was defined as the instant the right foot raised off the ground. This time was considered as "time zero" (T0) for all subsequent analyses.

Dependent variables

Kicking analysis

Two dependent variables described the kicking movement: Kicking accuracy and duration. To describe kicking accuracy, we adopted a three-point scale (Hart et al. 2014). Specifically, each kick was scored 1 (the ball missed the target), 2 (the ball reached the larger target zone), or 3 (the ball reached the smaller target zone). Kicking accuracy was calculated as the sum of the different scores across trials: The higher the score, the higher was kicking accuracy.

To analyze kicking duration, the kicking movement was arbitrarily divided into two successive phases: The backswing phase, reflecting the swing of the kicking leg in preparation for the downward motion towards the ball, started with the raising of the right ankle until the maximal backward position of the limb, whereas the shooting phase, reflecting kicking targeting, started from the maximal backward position until right foot contact with the ball toward the target (Kellis and Katis 2007). Foot contact was determined indirectly on the basis of the kinematics analysis, as the time of peak deceleration during the shooting phase.

Center of foot pressure (COP) and center of mass (COM) analysis

Four dependent variables described participant's postural behavior during the kicking task, separately for each of the two movement phases, i.e., backswing and shooting phases. It included calculation of mean mediolateral (ML) and anteroposterior (AP) amplitude (mm) and speed (mm s^{-1}) of COP displacements. The amplitude of COP displacements indicated the mean deviation of COP on the ML and AP axes. It is a global measure allowing to estimate overall postural performance. The mean speed of COP displacements was the sum of the displacement scalars divided by the sampling time, i.e., the duration of each movement phase. It represents the amount of activity required to maintain stability and provides a more functional measure of postural control (Geurts et al. 1993).

In addition to COP displacements, amplitude and speed of COM displacements were also obtained through the kinematics method which estimates COM displacements by the trajectory of the body segments (Mapelli et al. 2014). The biomechanical model of Winter (1990) was combined with anthropometric measurements and kinematics data to calculate the COM displacement on the ML and AP axes. The three-dimensional reconstruction of the markers kinematics was performed through off-line data processing techniques.

EMG analyses

The purpose of the EMG analysis was to determine whether the organization of postural muscular activity differed between the single and dual-task conditions for participants instructed to perform a similar kicking movement. More specifically, quantitative and temporal analyses of EMG activity were used to estimate the APAs occurring prior to the right kicking movement. This was accomplished by comparing the EMG activity of four muscles (BF, RF, GM, PL) of the supporting left limb. These muscles were considered as postural muscles because of their contribution to the maintenance of equilibrium in dynamic upright standing. To assess APAs, two dependent variables were used: (1) the EMG latency of the postural muscles and (2) the integral of anticipatory EMG activity (Aruin and Latash 1995a, b).

The onset of muscle activity for each trial was detected off-line on a monitor screen with a computer algorithm and confirmed by visual inspection. It was defined as the first visible rise of the rectified EMG signal, that is, when EMG activity exceeded the mean ± 2 standard deviations from the baseline signal in a time window from − 300 ms to + 50 ms with respect to T0 (Aruin et al. 2001; Woollacott and Shumway-Cook 2001; Strang and Berg 2007). The EMG latency of the postural muscles was defined as the delay between muscles' onset and movement onset, that is, when the right foot was raised off the ground (Bouisset and Zattara 1987b). Onset latencies for each postural muscle were then averaged across trials and conditions (Aruin and Latash 1995a; Santos and Aruin 2008; Eckerle et al. 2011).

To describe presumed changes in muscular activity, we also calculated the integral of changes observed in the baseline EMG activity of the postural muscles during APAs (Aruin and Latash 1995a). The following integral windows were used: $\int \mathrm{EMG}_{\mathrm{APA}}$ from − 100 ms to + 50 ms with respect to T0 for the APAs activity, and $\int \mathrm{EMG}_{\mathrm{Baseline}}$ from − 800 ms to − 650 ms with respect to T0 for the baseline muscular activity. The ratio $\Delta \int_{\mathrm{Integral}} = \int \mathrm{EMG}_{\mathrm{APA}} - \int \mathrm{EMG}_{\mathrm{Baseline}} / \int \mathrm{EMG}_{\mathrm{Baseline}}$ was used to characterize the anticipatory EMG changes in the activity of the postural muscles (Aruin and Latash 1995a, b; Mochizuki et al. 2004; Morris and Allison 2006; Strang and Berg 2007; Xiaoyan and Aruin 2007; Santos and Aruin 2008). Then, for each subject and for each muscle, all the $\Delta \int$ values were normalized by the maximal value of $\Delta \int$ (divided by $\Delta \int \mathrm{max}$). The across-subjects analysis of the changes in the muscle activity used normalized values of $\Delta \int$, in accordance with (Aruin and Latash 1995a, b; Shiratori and Latash 2001; Strang and Berg 2007). Normalization of anticipatory EMG integrals was adopted because it led to most reproducible among-subjects findings. This approach restricted $\int \mathrm{EMG}_{\mathrm{Integral}}$ to a range of − 1 to 1, where positive values indicated an increased activation in APA muscles and negative values corresponded to an APA inhibition (Shiratori and Latash 2001).

Intervals of integration were chosen based on previous studies that described APAs typically starting about 150–100 ms prior to the onset of EMG activity in the prime mover muscles (Kanekar et al. 2008). Furthermore, feedback effects were not expected during the first 50 ms after T0 (Shumway-Cook and Woollacott 2000; Shiratori and Latash 2001).

Statistical analyses

Kicking accuracy was submitted to a separate one-way (single vs. dual-task) analysis of variance (ANOVA). Kicking timing, COP, and COM dependent variables were submitted to 2 conditions (single vs. dual-task) × 2 movement phases (backswing vs. shooting) ANOVAs with repeated measures on both factors. Temporal analysis of the onset latency of the postural muscles was submitted to 2 conditions (single vs. dual-task) × 4 muscles (BF vs. RF vs. GM vs. PL) ANOVAs with repeated measures on both factors. However, to further determine which muscles accounted for the observed differences, a quantitative analysis, represented by EMG integral for each muscle, was submitted to separate one-way (single vs. dual-task) ANOVAs. The level of significance was set at $p < .05$. Post hoc pairwise comparisons (Tukey HSD) were performed whenever necessary to identify the specific differences in factors contributing to the variance observed in the data. All statistical computations were performed using a SPSS 10.0 software (SPSS Inc., Chicago, IL, USA).

Results

Kicking motion was achieved by a combination of muscle moments and motion-dependent moments, which can be analyzed through different kinematic or kinetic parameters. In Fig. 1, typical patterns of the various dependent variables are illustrated through the performance of one participant. These dependent variables were synchronized on T0, which determined the beginning of the kicking movement. To identify the APAs, we investigated the timing before T0. COP and COM displacement were calculated and analyzed separately for the two movement phases (backswing vs. shooting) and axes (AP and ML), yielded information on the effects of dual tasking on the interaction between posture and movement during the pointing lower limb movement.

Kicking performance

Kicking accuracy was lower in the dual- than single-task condition [$F(1,38) = 5.43$, $p < 0.05$, 37.5 ± 9.27 vs. 45.62 ± 12.03]. Total kicking timing was longer for

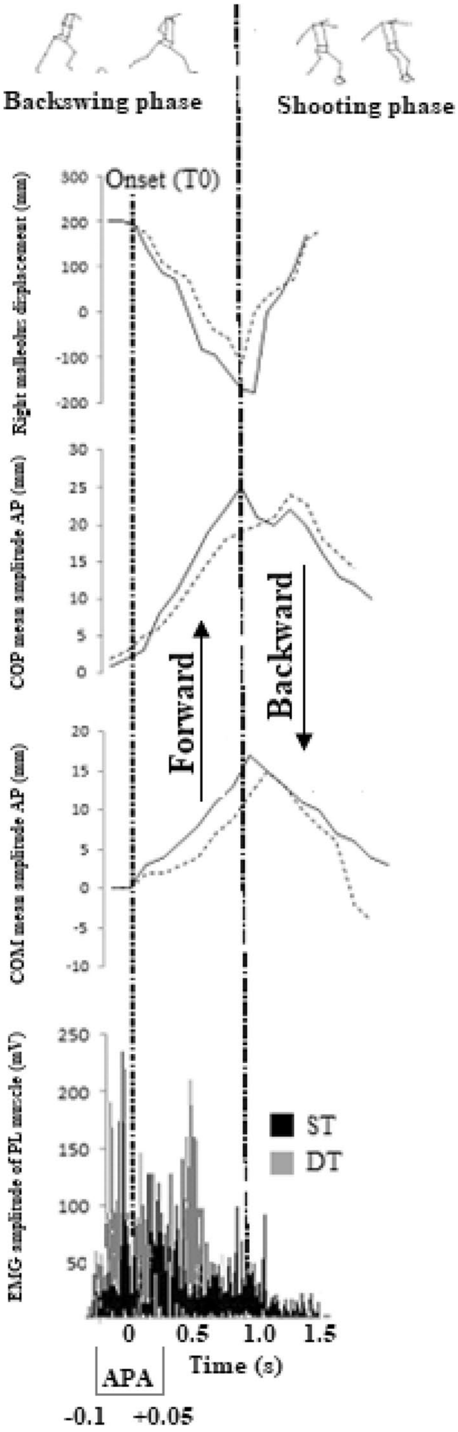

Fig. 1 Representative illustration of typical trajectories for one participant. Kinematics displacement of right malleolus on AP axis, COP mean amplitude, COM mean amplitude and EMG amplitude of PL muscle were temporally synchronized. The dashed and solid lines represent the single- and dual-task conditions, respectively

the dual- than single-task condition [$F(1,38) = 4.28$, $p < 0.05$, 1.01 s vs. 0.98 s, + 30ms]. More precisely, analysis of kicking timing showed main effects of condition [$F(1,38) = 4.76$, $p < 0.05$] and phase [$F(1,38) = 22.90$, $p < 0.05$]. A significant interaction of condition x phase was also observed [$F(1,38) = 12.89$, $p < 0.05$]. The post hoc revealed that duration of the backswing phase was longer in the dual- than single-task condition ($p < 0.001$), whereas duration of the shooting phase was similar whatever the condition (Fig. 2). On the other hand, no significant effect was observed when kicking duration was analyzed from T0 until foot contact with the ball toward the target ($p > 0.05$); therefore, confirming that movement speed was similar between the two conditions.

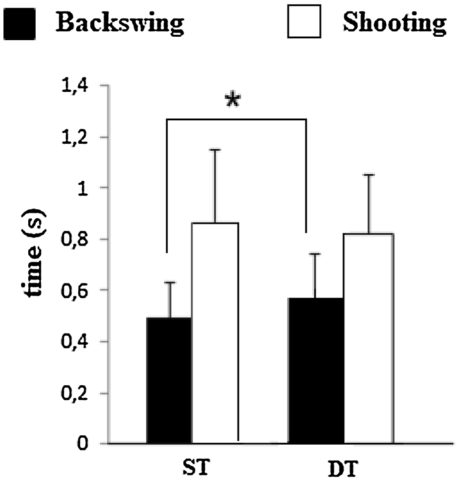

Fig. 2 Mean and standard deviation of kicking duration. The two single- and dual-task conditions are presented: backswing (black bars) and shooting (white bars) phases. *P* values between single- and dual-task conditions are reported: (*$p < 0.05$)

COP displacements

Analysis of AP mean amplitude showed a main effect of condition [$F(1,38) = 4.50$, $p < 0.05$] with a larger mean amplitude for the dual- than single-task. The main effect of phase [$F(1,38) = 2.23$, $p > 0.05$] and the interaction of condition × phase [$F(1,38) = 0.69$, $p > 0.05$] were not significant (Fig. 3a). On the ML axis, no significant effect was observed (Fig. 3b).

Analysis of mean COP speed on the AP axis showed a main effect of condition [$F(1,38) = 11.86$, $p < 0.05$] with a faster COP speed for the dual- than single-task. However, no main effect of phase [$F(1,38) = 0.60$, $p > 0.05$], and no interaction of condition × phase [$F(1,38) = 1.44$, $p > 0.05$] were observed (Fig. 3c). On the ML axis, no significant effect was observed (Fig. 3d).

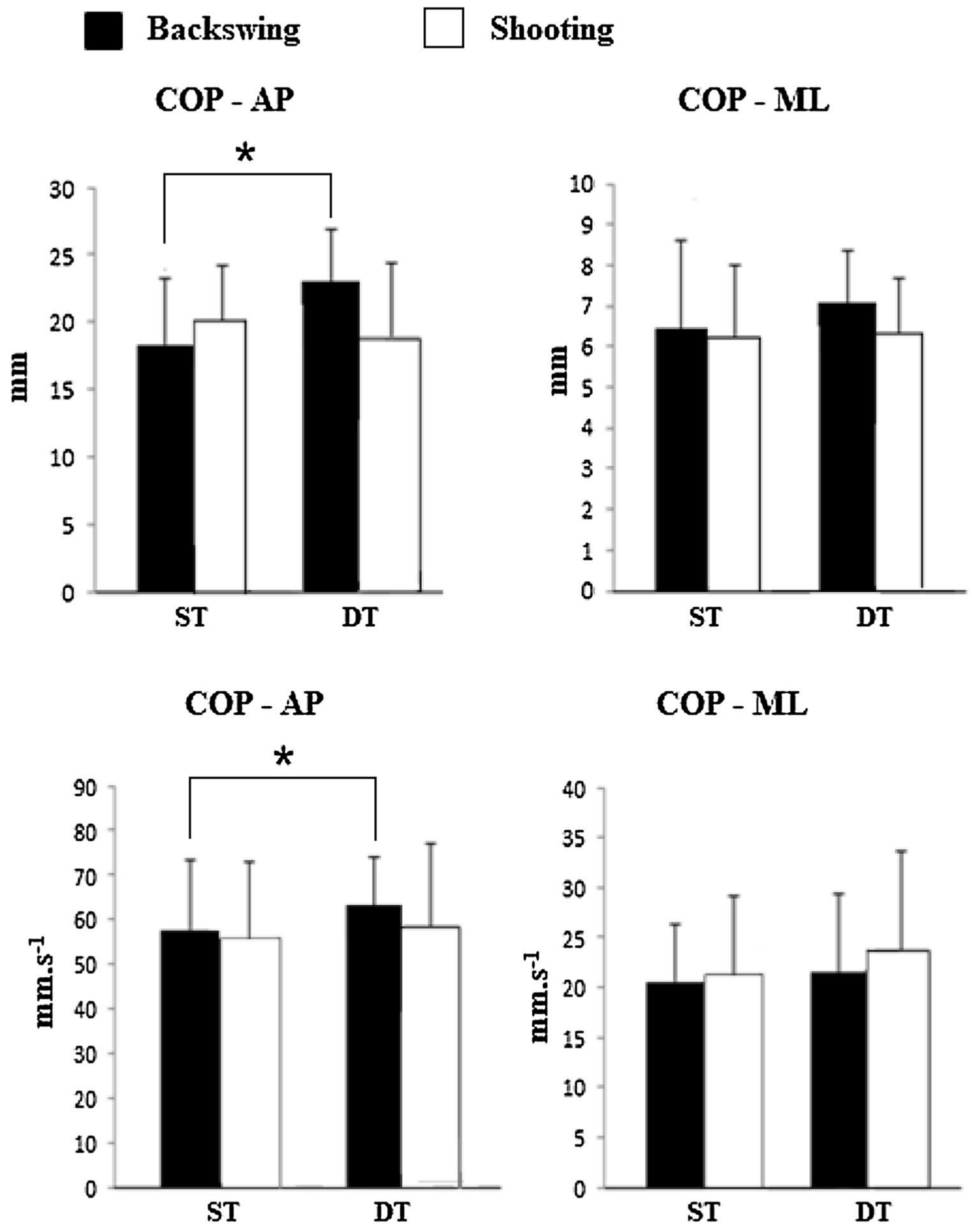

Fig. 3 Mean COP amplitude (upper figures) and speed (lower figures) and standard deviation on the AP and ML axes, for the single and dual-task conditions, respectively. *P* value are also reported (*$p < 0.05$)

COM displacements

Analysis of AP mean amplitude of COM displacement showed a main effect of condition [$F(1,38) = 10.50$, $p < 0.05$] with a larger mean amplitude of displacement for the dual- than single-task. The main effect of phase [$F(1,38) = 108.92$ $p < 0.05$] was also significant with a larger mean amplitude of displacement for the backswing than shooting phase. A significant interaction of condition × phase [$F(1,38) = 5.41$, $p < 0.05$] was also observed (Fig. 4a). Post hoc analysis revealed that the increase of AP COM displacement in the dual-task condition was larger in the backswing than shooting phase ($p < 0.0001$). On the ML axis, no significant effect was observed (Fig. 4b).

Analysis of mean COM speed of displacement on the AP axis showed a main effect of condition [$F(1,38) = 12.23$, $p < 0.05$] with a faster COM speed for the dual- than single-task. The main effect of phase [$F(1,38) = 23.09$, $p < 0.05$] was also significant with a faster COM speed for the backswing than shooting phase. A significant interaction of condition x phase [$F(1,38) = 6.06$, $p < 0.05$] was also observed (Fig. 4c). The post hoc showed that the increase of AP COM speed of displacement in the dual-task condition was larger in the backswing than shooting phase ($p < 0.01$). On the ML axis, no significant effect was observed (Fig. 4d).

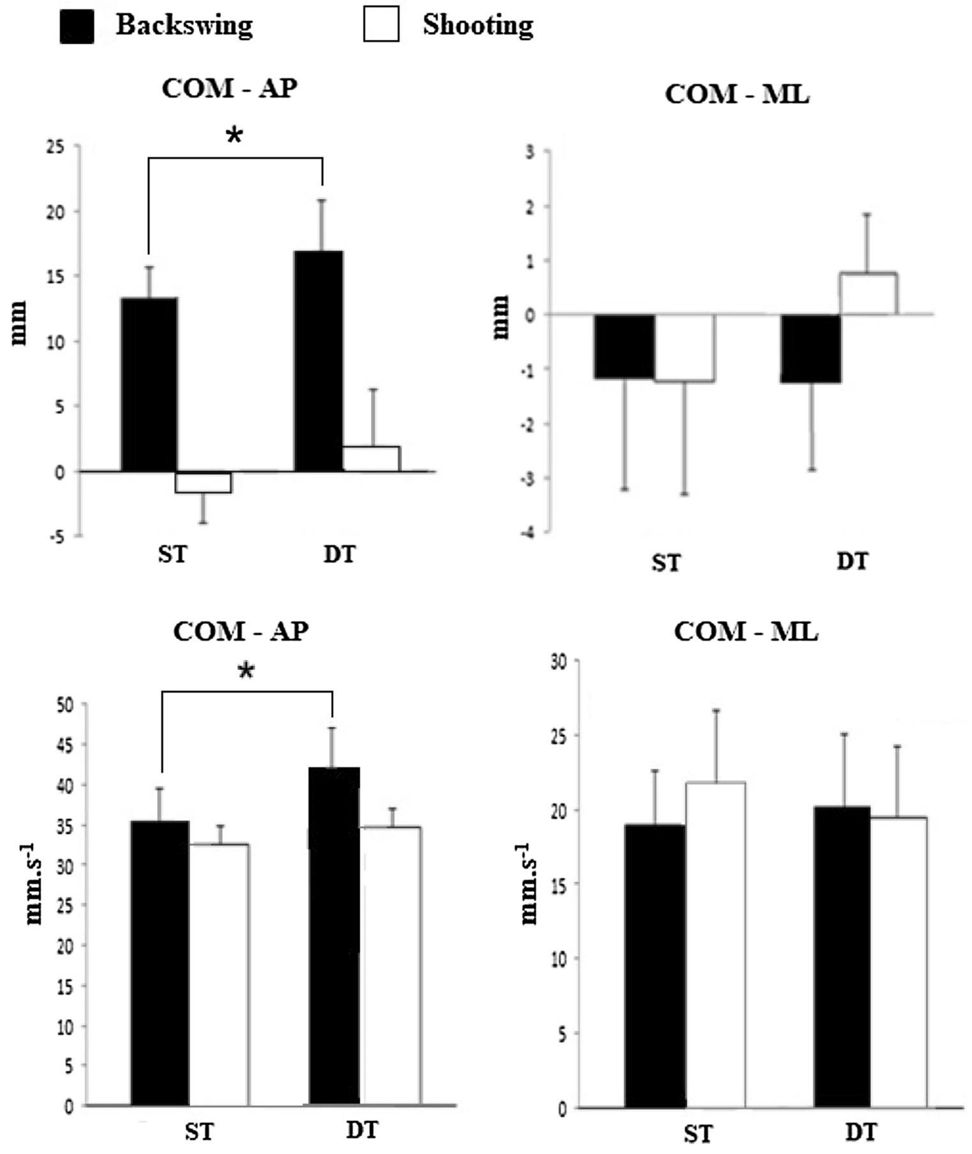

Fig. 4 Mean COM amplitude (upper figures) and speed (lower figures) and standard deviation on the AP and ML axes, for the single and dual-task conditions, respectively. *P* value are also reported (*$p < .05$)

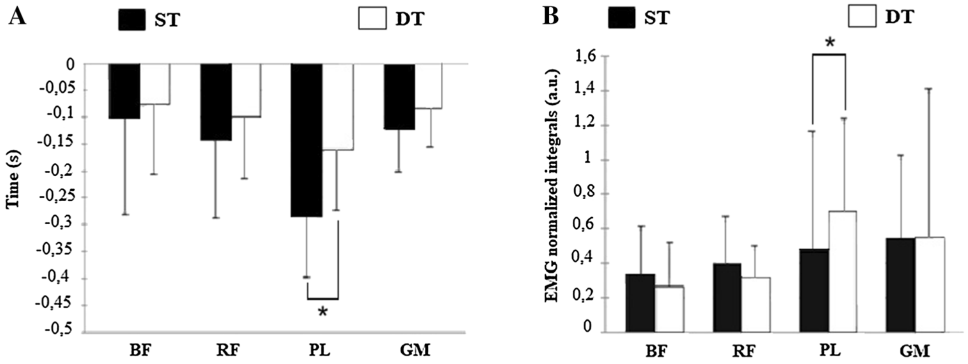

Fig. 5 Mean EMG onset latency and standard deviation (**a**) and mean EMG integral and standard deviation (**b**) for the four postural muscles and for the single- (black bars) and dual-task (white bars) conditions, respectively. The significant *p* values (*$p < 0.05$) were reported for comparisons between the two single- and dual-task conditions and the four postural muscles (BF, RF, GM, PL)

EMG analyses

Analysis of the onset latency of the postural muscles showed a main effect of condition [$F(1,38) = 6.18$, $p < 0.05$] with an earlier EMG burst before T0 for the single- than dual-task condition. The main effect of muscle was also significant [$F(3,114) = 14.23$, $p < 0.05$]. A significant interaction of condition × muscle [$F(3,114) = 2.73$, $p < 0.05$] was also observed (Fig. 5a). More specifically, post hoc analysis revealed that the mean latency of the BF, RF, and GM muscles was not different for the two conditions, whereas PL muscle showed a significant earlier onset in the single- than dual-task condition ($p < 0.0001$).

Normalized EMG integral from − 100 to + 50 ms showed that there was no effect of the dual-task condition for BF, RF and GM ($p > 0.05$). On the other hand, PL showed a smaller normalized EMG integral in the single- than dual-task condition [$F(1,38) = 6.44$, $p < 0.05$, Fig. 5b]. More specifically, the modification of muscular pattern was mainly observable in the dual-task condition (Fig. 1).

Discussion

As expected, the dual-task condition induced a decreased kicking accuracy, in accordance with previous reports showing a decreasing performance in such conditions (Shumway-Cook and Woollacott 2000; Carr et al. 2013; Rios et al. 2015). More specifically, analysis of kicking duration showed that participants spent more time in the dual- than single-task condition for performing the backswing movement (Carr et al. 2013; Hart et al. 2014), whereas duration of the shooting phase remained similar, whatever the condition. This suggested that with an additional cognitive load, participants dedicated more time to perform the backswing motion, to be as efficient as possible during the forward shooting movement toward the target. It also suggested that backswing motion was more controlled than shooting motion, which was rather ballistic, as suggested by the large increase of the right foot acceleration during the shooting phase.

It remains, however, that participants were less accurate in the dual- than single-task condition, as shown in previous studies (Lam et al. 2010; Gabbett et al. 2011; Gabbett and Abernethy 2012).

Analysis of COP displacement forward and then backward showed that participants presented a larger displacement in the dual- than single-task condition (Shumway-Cook and Woollacott 2000; Remaud et al. 2012). This behavior was more consistent during the backswing phase. Previous studies (Paillard et al. 2006; Matsuda et al. 2008) investigating groups of amateur and elite soccer players found an elevate variability on the ML axis and a reduced AP COP displacement for the amateur players, which somewhat contradicted the present results.

Analysis of COM displacement forward and then backward confirmed that participants presented a larger displacement in the dual- than single-task condition. This reflected a significant body inclination on that axis which was more consistent for the forward displacement during the backswing phase. This allowed reaching an adequate stability to perform the movement, even in situations in which there is an increased equilibrium constraint requiring to adopt a different strategy of COM motion (Horak and Nashner 1986; Crenna et al. 1987; Hilt et al. 2016).

Overall, COP and COM data obtained separately for each movement phase, suggested that different strategies performed by the CNS were adopted for maintaining postural stability during backswing and shooting motion, depending on the cognitive load.

In addition, to further determine whether the organization of postural muscular activity differed between the single- and dual-task conditions, EMG data allowed estimating the APAs to describe presumed changes in muscular activity.

Interestingly, in the dual-task condition, there was an increasing EMG activity of the plantar flexor. This muscle group has been shown to play an important role in the maintenance of postural control (Lundin et al. 1993), especially at the anterior limits of stability and may be more active when stability was altered by the dual-task, confirming the anticipatory contribution of these muscles mainly for the postural preparation time, which decreased as EMG onset of plantar flexor muscle was delayed.

More specifically, PL muscle showed a large magnitude of activation, mainly during dual tasking, which can be related with lateral stability, since participants would spend more time due to the premeditated prolonged backswing phase (Rios et al. 2015; Conceição et al. 2016).

Indeed, the different patterns of response observed for single- and dual-task conditions, that is, the combination of the temporal and quantitative EMG activity, resulted in overall similar APAs. This suggested that these two measures provide different information and had both to be computed for a correct estimation of the whole APAs.

In other words, increased APAs in dual-task condition, estimated by the quantitative EMG analysis, were compensated for by decreased APAs estimated by the temporal EMG analysis. However, this adaptation of APAs did not ensure an efficient performance of the movement, and therefore, was not functional as the performance was not the same between the two conditions, with a reduced kicking accuracy and an increased duration of the backswing phase in the dual-task condition.

This modification of EMG pattern activity was reminiscent of previous studies showing the existence of an adaptive strategy to perform the same task in different conditions

(Strang and Berg 2007; Mezaour et al. 2010). In other words, postural control and movement execution may require different modes of coordination, depending on the conditions. The present findings showed that movement speed was similar between the two conditions, suggesting that dual-task affected APAs directly, which rather supported the parallel control hypothesis.

On the other hand, the postural component started earlier than the focal component of motor behavior to minimize the perturbation of equilibrium caused by the oncoming focal movement (Frank and Earl 1990; Aruin and Latash 1995b; Conceição et al. 2016). This behavior was increased in the dual-task condition, as participants needed more time to reach an adequate postural stability allowing them to perform the movement as efficiently as possible, in accordance with previous studies (Rios et al. 2015; Hilt et al. 2016).

This pattern of motor responses suggested that a "parallel mode" for controlling the dynamic interactions between body segments was applied for both conditions.

Conclusion

The present results provided a better understanding of feedforward mechanisms involved in postural control when performing a kicking pointing movement toward a target. Depending on the condition, different strategies were adopted to perform the task. The dual-task condition modified directly the way APAs were generated, emphasizing that cognitive, postural, and motor processes worked dependently. We believe these observations pose fundamental questions regarding the behavior adopted by the different levels of sensory-motor organization necessary for an adaptable and optimal accurate movement.

Acknowledgements CAPES scholar-Process number BEX 14828/13-8. The authors would like to thank the contribution of Guillaume Chauvel, which was greatly appreciated. The authors also would like to thank the anonymous reviewers for helpful comments and suggestions.

Compliance with ethical standards

Conflict of interest Marcelo Guimarães Silva, Lucas Struber, José Geraldo Trani Brandão, Olivier Daniel and Vincent Nougier have no financial and personal relationships with other people or organizations that could inappropriately influence or bias their work in this study.

References

Archambault P, Pigeon PP, Feldman AG, Levin MF (1999) Recruitment and sequencing of different degrees of freedom during pointing movements involving the trunk in healthy and hemiparetic subjects. Exp Brain Res 126(1):55–67

Aruin AS, Latash ML (1995a) Directional specificity of postural muscles in feedforward postural reactions during fast voluntary arm movements. Exp Brain Res 103(2):323–332

Aruin AS, Latash ML (1995b) The role of motor action in anticipatory postural adjustments studied with self-induced and externally triggered perturbations. Exp Brain Res 106(2):291–300

Aruin A, Shiratori T, Latash ML (2001) The role of action in postural preparation for loading and unloading in standing subject. Exp Brain Res 138(1):458–466

Beilock SL, Carr TH, MacMahon C, Starkes JL (2002) When paying attention becomes counterproductive: impact of divided versus skill-focused attention on novice and experienced performance of sensorimotor skills. J Exp Psychol Appl 8(1):6–16

Bloem BR, Valkenburg VV, Slabbekoorn M, Willemsen MD (2001) The Multiple Tasks Test: development and normal strategies. Gait Posture 14(3):191–202

Bouisset S, Zattara M (1987b) Biomechanical study of the programming of anticipatory postural adjustments associated with voluntary movement. J Biomech 20(8):735–742

Carr BM, Etnier JL, Fischer KM (2013) Examining the time course of attention in a soccer kick using a dual task paradigm. Hum Mov Sci 32(1):240–248

Chew-Bullock TS, Anderson DI, Hamel KA, Gorelick ML, Wallace SA, Sidaway B (2012) Kicking performance in relation to balance ability over the support leg. Hum Mov Sci 31(6):1615–1623

Conceição JS, Schaefer FG, Santos GM, Keighley J, Dos Santos MJ (2016) Changes in postural control after a ball-kicking balance exercise in individuals with chronic ankle instability. J Athl Train 51(6):480–490

Crenna P, Frigo C, Massion J, Pedotti A (1987) Forward and backward axial synergies in man. Exp Brain Res 1987 65:538–548

Eckerle JJ, Ward RM, Berg WP (2011) The effect of load uncertainty on anticipatory muscle activity in a one-handed catching task. J Sport Exerc Psychol 33:suppl.67

Fourcade P, Hansen C, LeBozec S, Bouisset S (2014) Simultaneous postural adjustments (SPA) scrutinized using the Lissajous method. J Biomech 47(15):3645–3649

Frank JS, Earl M (1990) Coordination of posture and movement. Phys Ther 70(12):855–863

Gabbett TJ, Abernethy B (2012) Dual-task assessment of a sporting skill: influence of task complexity and relationship with competitive performances. J Sports Sci 30(16):1735–1745

Gabbett T, Wake M, Abernethy B (2011) Use of dual-task methodology for skill assessment and development: examples from rugby league. J Sports Sci 29(1):7–18

Geurts AC, Nienhuis B, Mulder TW (1993) Intra subject variability of selected force-platform parameters in the quantification of postural control. Arch Phys Med Rehabil 74(11):1144–1150

Hart N, Nimphius S, Piteri T, Newton R (2014) Leg strength and lean mass symmetry influences kicking performance in Australian football. J Sports Sci Med 13(1):157–165

Hilt PM, Berret B, Papaxanthis C, Stapley PJ, Pozzo T (2016) Evidence for subjective values guiding posture and movement coordination in a free-endpoint whole-body reaching task. Sci Rep 6(1):23868

Horak B, Nashner M (1986) Central programming of postural movements: adaptation to altered support-surface. Config J Neurophysiol 55(6):1369–1381

Kanekar N, Santos MJ, Aruin AS (2008) Anticipatory postural control following fatigue of postural and focal muscles. Clin Neurophysiol 119(10):2304–2313

Kellis E, Katis A (2007) Biomechanical Characteristics and Determinants of Instep Soccer Kick. J Sports Sci Med 6(2):154–165

Lam WK, Masters RSW, Maxwell JP (2010) Cognitive demands of error processing associated with preparation and execution of a motor skill. Conscious Cogn 19(4):1058–1061

Lundin TM, Feuerbach JW, Grabiner MD (1993) Effect of plantar flexor and dorsiflexor fatigue on unilateral postural control. J Appl Biomech 9:191–201

Ma S, Feldman AG (1995) Two functionally different synergies during arm reaching movements involving the trunk. J Neurophysiol 73(5):2120–2122

Mapelli A, Zago M, Fusini L, Galante D, Colombo A, Sforza C (2014) Validation of a protocol for the estimation of three-dimensional body center of mass kinematics in sport. Gait Posture 39(1):460–465

Massion J (1992) Movement, Posture and Equilibrium: Interaction and coordination. Progr Neurobiol 38(1):35–56

Massion J, Alexandrov A, Frolov A (2004) Why and how are posture and movement coordinated? Prog Brain Res 143:13–27

Matsuda S, Demura S, Uchiyama M (2008) Centre of pressure sway characteristics during static one-legged stance of athletes from different sports. J Sports Sci 26(7):775–779

Mezaour M, Yiou E, Le Bozec S (2010) Effect of lower limb muscle fatigue on anticipatory postural adjustments associated with bi-lateral-forward reach in unipodal dominant and non-dominant stance. Eur J Appl Physiol 110(6):1187–1197

Mochizuki G, Ivanova TD, Garland SJ (2004) Postural muscle activity during bilateral and unilateral arm movements at different speeds. Exp Brain Res 155(3):352–361

Monjo F, Forestier N (2014) Unexperienced mechanical effects of muscular fatigue can be predicted by the Central Nervous System as revealed by anticipatory postural adjustments. Exp Brain Res 232(9):2931–2943

Morris SL, Allison GT (2006) Effects of abdominal muscle fatigue on anticipatory postural adjustments associated with arm-raising. Gait Posture 24(3):342–348

Paillard T, Noe F, Riviere T, Marion V, Montoya R, Dupui P (2006) Postural performance and strategy in the unipedal stance of soccer players at different levels of competition. J Athl Train 41(2):172–176

Pozzo T, Stapley PJ, Papaxanthis C (2002) Coordination between equilibrium and hand trajectories during whole body pointing movements. Exp Brain Res 144(3):343–350

Remaud A, Boyas S, Caron G, Bilodeau M (2012) Attentional demands associated with postural control depend on task difficulty and visual condition. J Mot Behav 44(5):329–341

Rios JL, Gorges AL, Dos Santos MJ (2015) Individuals with chronic ankle instability compensate for their ankle deficits using proximal musculature to maintain reduced postural sway while kicking a ball. Hum Mov Sci 43:33–44

Robert G, Blouin J, Ruget H, Mouchnino L (2007) Coordination between postural and movement controls: effect of changes in body mass distribution on postural and focal component characteristics. Exp Brain Res 181(1):159–171

Santos MJ, Aruin AS (2008) Role of lateral muscles and body orientation in feedforward postural control. Exp Brain Res 184(4):547–559

SENIAM (1999) In: Hermens H, Freriks B, Merletti R, Stegeman D, Blok J, Rau G et al (eds) European recommendations for surface electromyography. RRD, The Netherlands

Shiratori T, Latash ML (2001) Anticipatory postural adjustments during load catching by standing subjects. Clin Neurophysiol 112(7):1250–1265

Shumway-Cook A, Woollacott M (2000) Attentional demands and postural control: the effect of sensory context. J Gerontol A Biol Sci Med Sci 55(1):M10-16

Strang AJ, Berg WP (2007) Fatigue-induced adaptive changes of anticipatory postural adjustments. Exp Brain Res 178(1):49–61

Wang J, Stelmach GE (1998) The coordination among body segments during reach-to-grasp action involving the trunk. Exp Brain Res 123(3):346–350

Winter D (1990) Biomechanics of human movement New York John Wiley.

Woollacott M, Shumway-Cook A (2001) Attention and the control of posture and gait: a review of an emerging area of research. Gait Posture 16(1):1–14

Xiaoyan L, Aruin AS (2007) The effect of short-term changes in the body mass on anticipatory postural adjustments. Exp Brain Res 181(2):333–346