Co-contraction training: myoelectric activity and recruitment strategies in an unorthodox resistance training

Received: 3 June 2021
Supplementary materials:
www.osf.io/a2pyb/
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Please cite as: Silva, N. R. S., Pacheco, M. M., Fujita, R. A., Villalba, M. M., Gomes, M. M. (2021). Co-contraction training: myoelectric activity and recruitment strategies in an unorthodox resistance training. *SportRχiv*. https://doi.org/10.31236/osf.io/jgsqa

All authors have read and approved this version of the manuscript. This article was last modified on June 3, 2021.

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ABSTRACT

Objective To elucidate the muscle recruitment patterns and interindividual variability during co-contraction training sessions for lower limbs.

Methods Ten active male young adults underwent two days of tests, in which they performed, for each leg, a maximal isometric voluntary contraction protocol followed by a co-contraction training set. We acquired myoelectric (EMG) activity from the sartorius, biceps femoris long and short heads, semitendinosus, semimembranosus, rectus femoris, vastus lateralis and vastus medialis and tensor facia latae during both protocols. We used iterative HLM analyses and bootstrap ANOVAs to explain within and between participant variances.

Results On average, participants started recruiting 36% of their maximum EMG amplitude, showing decays of 0.41% per repetition and increasing 7.45% from day 1 to day 2. Participants who started with higher recruitment showed greater decays over repetitions and vice-versa. The training stimulated similarly the ratio of participants' flexors and extensors. However, participants demonstrated different average muscle recruitment patterns with some individuals modifying, largely, their recruitment over repetitions/days. Between and within-variability in recruitment pattern was maintained throughout repetitions and days. We found no consistent similarity in terms of pairs of participants as to find common types of recruitment.

Conclusion Co-contraction training seems to be effective to recruit thigh muscles of both legs along an entire set of repetitions and days. Despite the accounted variations in intramuscular recruitment, co-contraction training evokes similar muscular in flexor's and extensor's recruitment among participants.

Keywords: Co-activation, Self-resistance exercise, EMG

INTRODUCTION

The "facility-based" strength training cannot be considered the unique alternative for strength improvement. Phenomena urge for forms of training that can be self-managed and require no equipment: the growth of the older population institutionalized which will hardly have access to in-person and at-facility exercise programs (Institute of Medicine Food Forum, 2010); the increasing requirement for training programs that deal with microgravity environments (English et al., 2019; Mulavara et al., 2018; Ploutz-Snyder, 2016); the need of social distancing due concern with more frequent pandemics (WHO, 2020). In this sense, an alternative is the co-contraction training, characterized by voluntary simultaneous contraction of agonist and antagonist muscle groups around a given joint (Driss et al., 2014; MacKenzie et al., 2010; Serrau et al., 2012). Thus, each muscle group works against each other, providing mechanical resistance to conduct a strength training session without external load.

Studies have demonstrated the usefulness of the co-contraction training for strength improvements (up to 22% and 13% for elbow flexors and extensors, respectively) after four to twelve weeks of training (Driss et al., 2014; MacKenzie et al., 2010; Maeo et al., 2014a; Zbidi et al., 2017). Despite evidence showing up to 76% of maximal myoelectric (EMG) activity on the involved muscles (MacKenzie et al., 2010; Maeo et al., 2014a), it is unknown how the co-contraction training affects the effort distribution among the muscles involved in a co-contraction training set.

Previous studies showed variable contributions of muscles groups during submaximal and maximal contraction tasks within and between-participants, given anatomical differences and control strategies (e.g., Pincivero et al., 2000; Santello & McDonagh, 1998; Visscher et al., 2017). Once the isometric co-contraction training requires a zero-net torque, joints that involve many muscles can enlarge the span of contribution possibilities modifying muscle recruitment patterns. Previous studies have only focused on exploring co-contraction training benefits on joints with few muscles involved (i.e., elbow). Even if intra and inter-participant variability were considered, the limitations in these studies forbids comprehension of the human muscle-joint system's complexity (Bernstein, 1967), restricting understanding of the participant's response.

Therefore, it is warranted to characterize how the co-contraction training stimuli different participants through repeated sessions, to describe the range of possibilities that this training encompasses–especially considering that such range will define, through EMG behavior, the training efficiency (Vigotsky et al., 2017). Thus, we aim to characterize the co-contraction training, showing its stimulus on the EMG activity, investigating the variability between-/within-participants in the patterns of average and individual EMG activity. Specifically, this study elucidates (a) the demands of the co-contraction training on muscle recruitment over a training series; (b) the muscle recruitment behavior of knee flexors and extensors over a set of co-contractions; and (c) the variability on EMG magnitude between muscles in the same muscle group during the co-contraction training. We expect to find the range of variation demonstrated between and within participants and identify how the training constrains the stimuli: a thorough characterization of the paradigm.

METHODS

Research design

Cross-sectional design.

Participants

Ten active male young adults (minimum of one year practicing physical exercises at least three times a week) participated in this study. No participants reported orthopedic injuries on the lower limbs–on the previous six months–or any health problem that could affect performance. All procedures were approved by the local ethics committee and accord to the Helsinki Declaration.

Experimental Approach

All procedures below were followed equally for the first and the second day (five days later).

Maximum isometric voluntary contraction (MIVC)

The first leg to be tested was aleatorily chosen. The participants warmed-up with two sets of 20 repetitions of bodyweight full squat (1:1 second cadency, resting 60 seconds between sets). Then, the EMG sensors were placed over the participant's skin.

The participants remained seated and strapped by the chest and waist on the equipment chair (Biodex System 4Pro, Biodex) maintaining the tested knee flexed at 60º. They performed two submaximal trials of knee extensions and flexion for familiarization and rested for 30 seconds. Then, the participants performed three maximum isometric knee extensions and flexions in an interspersed way. Each MVIC lasted five seconds, with 60 seconds of rest between them.

Co-contraction set protocol

Five minutes of resting after the MIVC test, the participant was instructed to co-contract his thigh muscles as strong as possible keeping the knee angle fixed (60º). The evaluator visually controlled the knee angle and instructed each participant to use the isokinetic device arm as a position reference. For familiarization, the participant performed up to three co-contractions in a row followed by 30 seconds of rest. Then, the participant performed 20 four-seconds repetitions (with a four-seconds rest between repetitions) of maximum co-contraction, controlled by a metronome app (Intervals Pro, FourthFrame Technologies LLC). Finishing the 20 repetitions, the participant rested for five minutes and all procedures were repeated with the other leg, including the MIVC test.

Myoelectric Activity Acquisition and Processing

We used a wireless electromyography device (Trigno Lab Wireless; Delsys, 2000Hz) to collect EMG data from three knee extensors (rectus femoris, vastus lateralis and vastus medialis), five knee flexors (sartorius, biceps femoris long and short heads, semitendinosus, and semimembranosus), and the tensor fascia latae, following Hermens et al. (2000), and Perotto et al. (2011) recommendations. The sensors were strapped with a TheraBand tape to avoid sensor displacements on the skin. Visual inspection of the data served the purpose to remove small artifacts from the EMG time series (less than 192 ms). We removed from analysis repetitions with artifacts larger than 192 ms (13.75% of the data was removed in this process).

We extracted the EMG activity from each repetition with a Matlab algorithm developed for this

DOI: 10.31236/osf.io/jgsqa

purpose (Supplementary File) and filtered the data with a second order bandpass Butterworth filter (10-500Hz). For each repetition, we considered the root mean square (RMS) of the signal as the muscular activity magnitude. The data were normalized by the maximum RMS value of each muscle in the MIVC protocol of the same day.

Statistical Analysis

All statistical analyses followed the same procedure. Considering that within-participants data could be clustered, we evaluated the necessity of performing a hierarchical linear model (HLM, Raudenbush & Bryk, 2001) by considering the intra-class correlation (ICC) of the null-model. For all instances that the ICC was above 0.15 and below 0.9 (indicating both within and between-participant variance to be explained) (Hox, 2010), we performed iterative HLM analyses with a backward procedure (based on the Bayesian Information Criteria) to arrive at the simplest model to explain the given data. For any variables that did not need the use of the HLM, bootstrap ANOVAs were used with 2000 iterations (see step-by-step of each analysis in Supplementary Files).

Results

Change in the Average Muscle Recruitment Through Repetitions

To investigate the magnitude of the stimuli provided by the training paradigm, we investigated the change in overall muscle recruitment in the co-contraction training paradigm. For this, we averaged, per repetition, the RMS of all muscles and evaluated the effect of repetition number, legs, and days. The resulting HLM (R2=0.84) revealed that participants start, on average, recruiting 36% of their maximum EMG amplitude (standard error [S.E.]=5.61, t[689]=6.47, p<.001), show a decay of 0.41% per repetition (S.E.=0.15, t[689]=2.67, p=.007), and increase 7.45% from day 1 to day 2 (S.E.=1.95, t[689]=3.81, p<.001) (Figures 1a and 1b). Nevertheless, participants varied largely between them in their initial EMG amplitude ([S.D.]=17.64%), change per day (S.D.=6.01%), change per repetition (S.D.=0.47%) and differences between legs (S.D.=4.92%). Finally, the HLM model demonstrated a negative correlation between initial recruitment and change over repetitions (r≈-1) indicating that those who started with higher recruitment, showed large decay in recruitment over repetitions and vice-versa.

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Consistency Between Flexors-Extensors

To investigate the training stimulus between participants on flexors and extensors, we performed

DOI: 10.31236/osf.io/jgsqa

a principal component analysis between the average flexor and average extensor recruitment. Then, we evaluated how the relation between flexor and extensor recruitment (capturing ≈86.57% of the variance, see the Supplementary File) was modified given days and legs (Figure 1c). In this case, the ICC was below 0.15 (≈0.06) and, thus, participants are similar in the flexor/extension relation. The bootstrap ANOVA revealed no effects of day (F[1,9]=0.53, p=.528), leg (F[1,9]=0.13, p=.758), or interaction between them (F[1,9]=0.14, p=.743). Participants maintained a constant relation of 1.15% extensor recruitment to 1% flexor recruitment.

Consistency Between Individual Muscles: Within Participant Consistency

The constant relation between flexors and extensors is expected given the zero-net torque task demand. However, individual flexors and extensors are free to vary within such average activation. Thus, we investigated how participants maintained their muscle pattern recruitment in terms of consistency and variability. Participants demonstrated different muscle recruitment patterns (Figures 2a and 2b) and were more (Figure 2c) or less (Figure 2d) variable through repetitions. Considering the group, participants varied more in some muscles (TFL, Figures 2e and 2f) than others (VL).

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Regarding consistency, we averaged each muscle recruitment considering three “blocks” during training (beginning: repetitions 1 to 6, middle: 8 to 13, and end: 15 to 20) and performed the normalized dot product (Allen et al., 2019) between the beginning of day 1 and the other blocks from day 1 and 2, and from the beginning of day 2 to the other moments of day 2 (see Figure 3). Values below 0.9 demonstrate non-similar recruitment patterns. Considering the beginning of day 1, four participants (P1, P5, P6, P8) decreased, continuously, the similarity in their recruitment pattern over blocks for the right leg and one participant showed large differences from the middle of day 1 (P9). Among these five participants that presented differences from day one on the right leg, only three of them (P1, P6, P9) showed such differences on the left leg. Considering the beginning of day 2, only one participant showed changes in the recruitment pattern.

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These results revealed that in the initial day of practice, more participants modified their average recruitment pattern. This change decreased in the second day.

Consistency Between Individual Muscles: Within Participant Variability

Decreases in muscle recruitment are possible if participants found efficient ways to perform the training. However, they might maintain the average recruitment while varying largely over trials. To investigate this possibility, we calculated the radius of the 9-dimensional circle formed of all repetitions of each moment (beginning, middle, end) per day as a measure of within-participant variability in their recruitment pattern (Allen et al., 2019). The resultant HLM model included only the intercept; participants varied similarly over blocks of the experiment.

Consistency Between Individual Muscles: Group Variability

We also investigated whether (despite the large variation in individual patterns allowed between participants) participants demonstrate similar recruitment patterns. This is highly relevant to understand the training stimuli across participants. For this, we calculated the radius of the 9-dimensional circle formed of the average recruitment pattern of all participants considering the repetitions of each moment (beginning, middle, end) of each day as a measure of between-participant variability in their recruitment pattern. Figure 4a shows the variability between-participants and its bootstrap confidence interval (1000 iterations). The group did not show variability changes over blocks, days or legs.

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To investigate how such variability represents disparities between participants, we calculated the normalized dot product between each pair of participants for each block, day, and leg (see Figure 4b). There is not a systematic pattern in terms of pairs of participants (their similarity depends on the days and moment) but, despite majority of values ranging from 0.8 to 1, we find pairs with values as low as 0.3.

DISCUSSION

The present study aimed to fully characterize the co-contraction training through analyses of overall muscle recruitment, and between-/within-participant analyses of individual and group muscle through repetitions, days and limbs. Our general findings are that the training stimuli flexors and extensors (as a group) similarly between participants while being specific in terms of overall magnitude and muscle pattern recruitment. To our knowledge, this is the first study encompassing the complexity of movement control in evaluating a strength training protocol.

The average muscle recruitment in our study was of 36% of MIVC. This value is lower in terms of other co-contraction studies (between 48 to 78%, Maeo et al., 2014; Serrau et al., 2012; Tyler & Hutton, 1986) and in terms of conventional training paradigms (> 36%, Andersen et al., 2018; Contreras et al., 2015; Wilk et al., 1996). Clearly, we need to acknowledge that the co-contraction training is unusual and might induce–at least initially–less recruitment than other paradigms. Perhaps, consequently, we found a general "practice" effect of 7% on muscle recruitment after a single practice. This corroborates Maeo et al. (2014) who found EMG increments up to 31% after four weeks of training in the same paradigm. This general increment in EMG activity supports the employability of the paradigm: independent of initial experience, continuous practice without external loading will lead to increased muscle recruitment and, consequently, positive strength adaptations (Driss et al., 2014; Maeo et al., 2014a; Zbidi et al., 2017).

Another advantage of the method lies in the fact that the 0.41% of recruitment decrement over repetitions does not necessarily lead to the interruption or end of training. On average, a participant would reach, at least 28.2% of their maximum muscular recruitment at the end of the set (Figures 1a and 1b). Traditional strength training methods such as the drop sets seek to maintain the muscle recruitment along repetitions by lowering the mechanical resistance (Schoenfeld, 2011). In contrast, the co-contraction seems to self-regulate this mechanical resistance through fatigue, once the ratio of muscular recruitment of knee flexors and extensors is maintained over set and days (Figures 1c). Further, our analyses show that those who initially fail to reach high levels of recruitment at first, actually increase their recruitment over repetitions–another positive compensation that requires no external intervention.

Despite the consensus in the area of motor behavior on within-/between-participants "motor styles" in a range of tasks (Vidal & Lacquaniti, 2021), comparisons between exercises and training protocols largely ignore how participants vary in their responses (Boyer et al., 2021; Horst et al., 2020; Torres-Oviedo & Ting, 2010). Despite the work of specific laboratories (Crouzier et al., 2019; Fujita et al., 2020), we have difficulty to find studies that evaluate how the same participant responds differently over time, and how different participants differ under the same paradigm.

Within-participant changes in muscle recruitment demonstrate flexibility to accommodate different task demands (see Allen et al., 2019; Sawers et al., 2017). Participants who changed their patterns (Figure 3) cannot be differentiated by their initial overall recruitment (P1: 11%, P6: 56%, P9: 31%); these changes can refer to processes such modifications to accommodate metabolic cost, attempts to increase recruitment or stabilization of performance–all can lead to transitions to new forms of muscle coordination (at least theoretically, Kelso, 1995). The fact that less changes were observed in the second day demonstrate a more functional muscle recruitment pattern (see Kargo & Nitz, 2003; Radhakrishnan et al., 2008, for how myoelectric activity changes improving performance). The untouched within-participant variability can speak to the continuity of search for more stable recruitment patterns or even to strategies to dissipate fatigue between muscles (Evetovich et al., 2007; Palmerud et al., 1995, 1998). Variability between participants is linked to differential motor repertoire. This results from previous experiences (favoring given muscle synergies or increasing strength differentially among muscles), physiological and biomechanical differences (muscle insertions, lever arm lengths, neural drive), and many others (Pincivero et al., 2000; Santello & McDonagh, 1998; Visscher et al., 2017).

A major factor allowing emergence of within and between-participant variability is the task. Pacheco et al. (2019) explains that when tasks are redundant, participants exploit the potential solutions as to accommodate their own intrinsic tendencies. Furthermore, even when more restrictive tasks are performed, participants exploit less relevant phases of the movement (Ting et al., 2015). In the present task, we anticipated that the zero-net torque would allow variability as any combination of flexors and extensors maintaining this result was permitted. This feature could be interpreted as supporting conventional training (as non-zero net torques are required over the movement). However, through joint torque compensations (and consequently muscle recruitment), participants can also vary leading to different stimuli in the same task (Hug et al., 2010).

It is important to highlight that, only through the analyses of the differences, it might be possible to understand the commonalities of the training. Figures 2e and 2f demonstrate how each muscle varies. The muscle recruitment pattern in the knee extensors is more consistent between participants (most participants maintain RF and VM as the basis for extension) when compared to the general results of the knee flexors and the TFL. Indeed, it is observing the high participation of the TFL (and large between-participants variability) that we find the unusual nature of the task induces participation of non-involved muscles–which is not a bad feature necessarily.

Acknowledges and Limitations

This is the first study to detail through group and individual analyses of overall and individual muscle recruitment patterns in the co-contraction training. To the best of our knowledge, this study is one of the few that encompasses the complexity and capabilities of the human movement system in understanding muscle control (see Aeles et al., 2021; Hug et al., 2010). Our methods were chosen specifically to evaluate and demonstrate potential recruitment patterns among the knee extensors and flexors during the co-contraction training paradigm. Indeed, the observance of differences and commonalities among participants supports our decision.

We acknowledge the limitations and potential extensions of our study. Despite the consistent compensation between flexors and extensors, we have reasons to believe that muscles primarily related to other joints might participate in the exercise, modifying the relation between muscles. Considering biarticular muscles such as the rectus femoris and hamstring muscles, future studies should investigate potential "interferences" from muscles at the hip and/or ankle levels. Also, future studies must account for such between-/within-variability by increasing sample size, adding other populations, increasing time between tests, and measuring aspects that would help to understand the source of individual differences.

Key messages

What are the findings?

- Co-contraction training induces, on average, up to 43% of maximal EMG of the thigh muscles during training, without exposing the participant to injuries due its capability to adjust self-resistance.
- Despite recruitment variability between/within participants, the recruitment over the main flexors and extensors is maintained along the entire set of repetitions, days and between both legs.
- Despite the presence of variations intramuscular recruitment patterns between-subjects, co-contraction training seems to evoke certain similarity of muscular recruitment patterns among

participants.

How might it impact on clinical practice in the future?

- The present study supports the idea that the co-contraction training is a reliable and consistent option for strength training when there is no access to equipment, specialized facilities, and/or gravity.

Funding information

This study was financed in part by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) – (Finance Code 001) and by the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) – (Finance Codes: 140064/2021-4 (RAF); 140098/2020-8 (MMV)).

Data and Supplementary Material Accessibility

Supplementary material of this manuscript can be found at www.osf.io/a2pyb/

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FIGURE 1

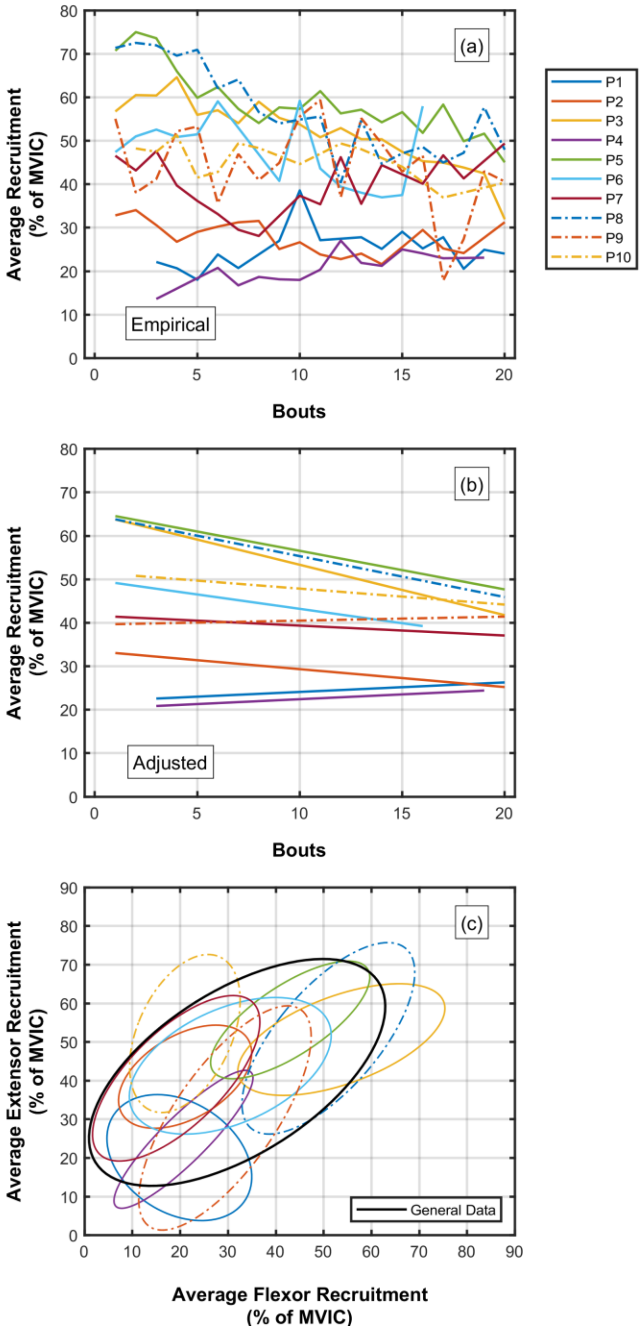

Figure 1: (a) Average muscle recruitment of each participant, for each of the twenty bouts during the first day; (b) Adjusted average muscle recruitment of each participant, for each of the twenty bouts during the first day; (c) Knee flexors and extensor mean recruitment relation, for each of the twenty bouts during the sessions, for both legs and days.

FIGURE 2

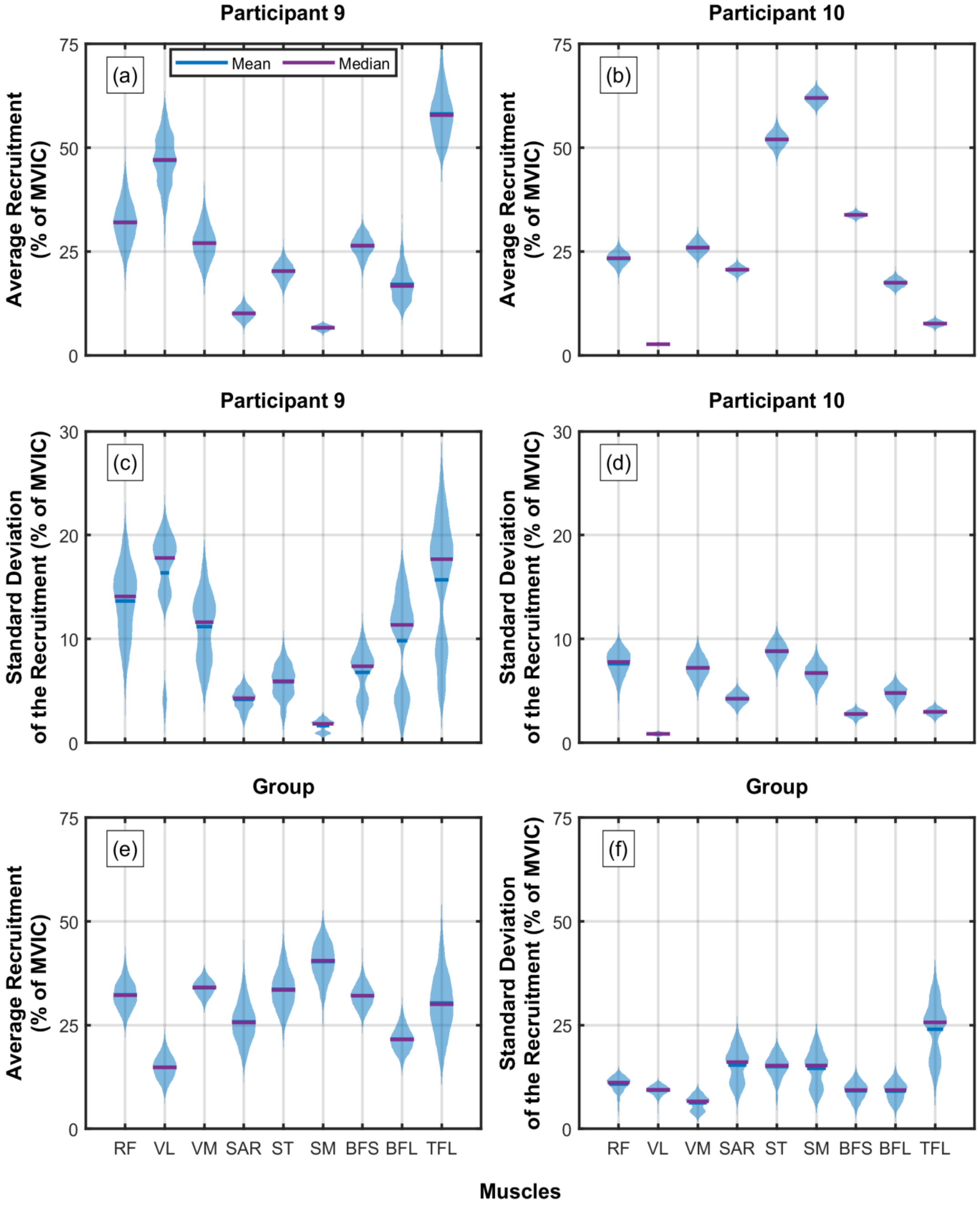

Figure 2: (a and b) Participant's 9 and 10 bootstrapped distributions of the average muscle recruitment, with the mean (blue) and median (purple) values, for all muscles captured during all repetitions of both legs and days; (c and d) Participant's 9 and 10 bootstrapped distribution of the muscular standard deviation recruitment, with the mean (blue) and median (purple) values for all muscles captured during all repetitions of both legs and days; Group bootstrapped distribution of average (e) and standard deviation (f) recruitment, with the mean and median values

for all muscles captured during all repetitions of both legs and days. Before the bootstrapping procedures all contributions were normalized in terms of the overall magnitude of activation (divided by the norm) as to grasp variations in terms of the relative contribution of each muscle to the coactivation pattern. All distributions considered only the first day and the right leg. RF: Rectus femoris muscle, VL: Vastus lateralis muscle, VM: Vastus medialis muscle, SAR: Sartorius muscle, ST: Semitendinosus muscles, SM: Semimembranosus muscle, BFS: Biceps femoris (short head) muscle, BFL: Biceps femoris (long head) muscle, TFL: Tensor fasciae latae muscle.

FIGURE 3

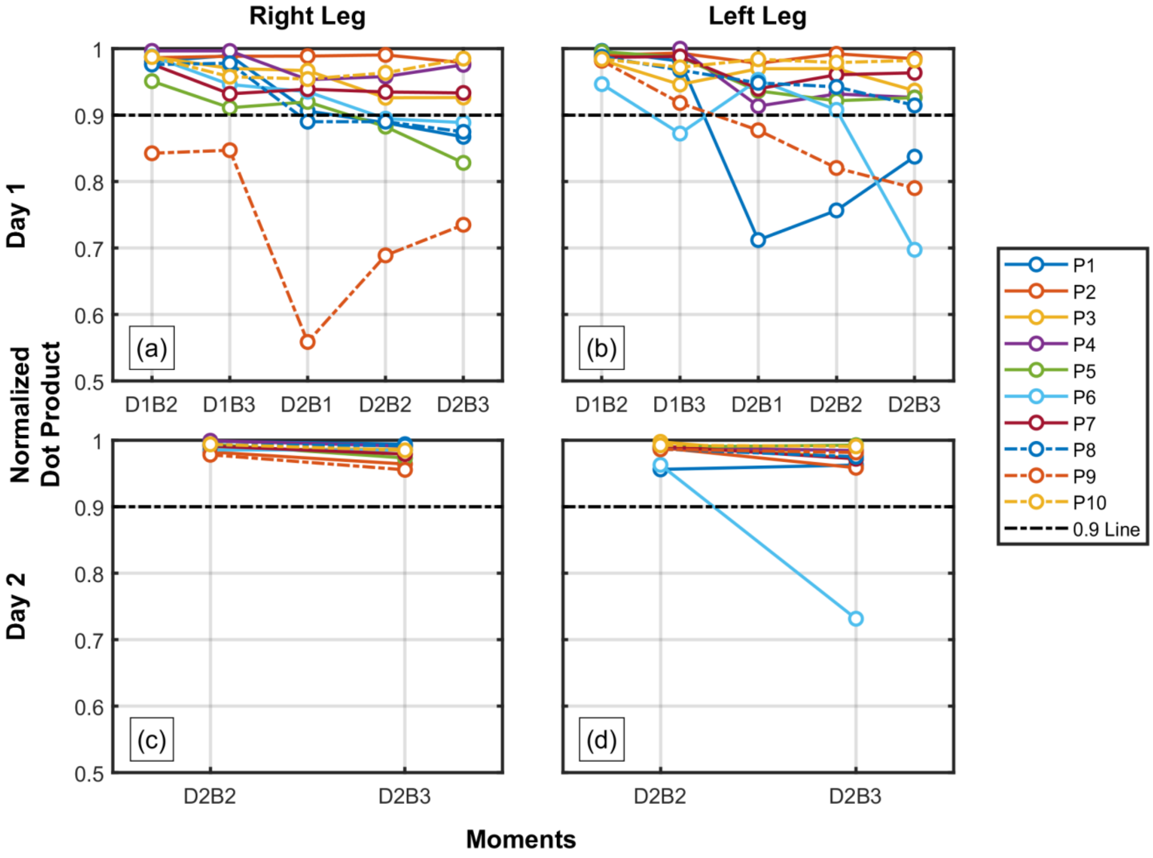

Figure 3: Participants muscle recruitment correlation coefficient behavior between day-one block-one and the following blocks of bouts of day one and two, for the right (a) and the left leg (b); Participants muscle recruitment pattern's correlation coefficient behavior between day-two, block one and the following blocks of bouts for the right (c) and the left leg (d). D1B1: Day one block one, D1B2: Day one block two, D1B3: Day one block three, D2B1: Day two block one, D2B2: Day two block two, D2B3: Day two block three.

FIGURE 4

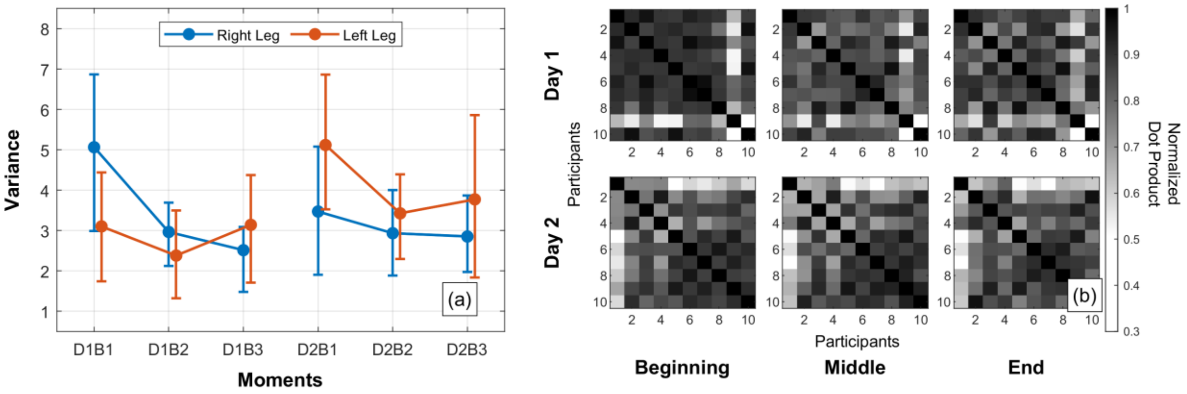

Figure 4: (a) Mean and confidence interval of the muscular recruitment variability between-individuals, for each of the blocks of bouts, for both days and legs; (b) Normalized dot product of muscular recruitment patterns between each pair of individuals, for each day and block of bouts. D1B1: Day one block one, D1B2: Day one block two, D1B3: Day one block three, D2B1: Day two block one, D2B2: Day two block two, D2B3: Day two block three.

DOI: 10.31236/osf.io/jgsqa