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Individual Control Strategies in Training: Myoelectric activity and recruitment strategies in the co-contraction training

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HIGHLIGHTS
- We studied the intra-/inter-individual myoelectric variability in the co-contraction training.
- Individuals maintain a common flexor/extensor ratio.
- Variability within-/between individuals is maintained over days.
- Individuals differ largely in their muscle activation pattern.
- The overall EMG activation dynamics is individual.

ABBREVIATIONS

BFL	Biceps femoris (long head) muscle
BFS	Biceps femoris (short head) muscle
HLM	Hierarchical Linear Model
ICC	Intra-class correlation
MIVC	Maximum isometric voluntary contraction
PCA	Principal component analysis
r	Pearson's correlation measures
RF	Rectus femoris muscle
RMS	Root mean square
SAR	Sartorius muscle
SM	Semimembranosus muscle
ST	Semitendinosus muscles
TFL	Tensor fasciae latae muscle
VL	Vastus lateralis muscle
VM	Vastus medialis muscle

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BACKGROUND: The literature in motor control has abundant evidence on within-/between-person variability when it comes to control strategies in several behaviors - which largely influences intervention outcomes. Despite being an intervention itself, strength training paradigms are yet to be analyzed beyond the average behavior. Based on myoelectric activity (EMG) analyses, this study emerges as a descriptive analysis on how the co-contraction training paradigm provides stimuli for strength training of knee extensors and flexors.
AIM: Considering the potential large interindividual variability in muscle activation patterns during resistance training, we explored the co-contraction paradigm considering the individual characteristics.
METHOD: Ten active male adults participated in two days of co-contraction training paradigm with their EMG activity collected (sartorius, biceps femoris long and short heads, semitendinosus, semimembranosus, rectus femoris, vastus lateralis and medialis and tensor fascia-latae).
RESULTS: On average, participants recruit 36% of their maximum EMG amplitude, decay 0.41% per repetition but increase 7.45% between sessions. The training stimulated similarly the knee flexors and extensors EMG ratio of all participants. However, participants demonstrated different average muscle recruitment patterns with few individuals modifying, largely, their recruitment over repetitions/days. Between and within-variability in recruitment pattern was maintained throughout repetitions and days.
CONCLUSION: Thus, the co-contraction training demonstrated sufficient muscle activation to be employed and evoked similar muscular recruitment between agonists and antagonists. To the best of our knowledge, this is a pioneer study encompassing the complexity of movement control in evaluating a strength training protocol.

KEYWORDS: Co-activation | Self-resistance exercise | EMG | Force Control | Practice Effect

INTRODUCTION

The "facility-based" strength training paradigm cannot be considered the unique alternative for strength improvement. A range of phenomena urge for training paradigms that could be self-managed, requiring no equipment: the growth of institutionalized/aged population with limited access to in-person and at-facility exercise programs [1]; the increasing requirement for training programs that deal with microgravity environments [2–4]; the need of social distancing due to potentially more frequent pandemics [5]. An alternative for traditional strength training is the co-contraction training. It is characterized by voluntary simultaneous contraction of agonist and antagonist muscle groups around a given joint [6–8] providing enough mechanical resistance to conduct a strength training session without external load. Studies have demonstrated the usefulness of the paradigm for strength improvement: up to 22% and 13% for elbow flexors and extensors, respectively, following four to twelve weeks of training [6,7,9,10].

Nonetheless, the evidence supporting the co-contraction training paradigm comes from studies on upper limbs. When Maeo and Kanehisa [11] focused on testing the maximum activation during voluntary co-contraction of the muscles around the knee and ankle joint during two bouts of five seconds, they observed low activation in two extensor muscles (31.9±9.7% of the rectus femoris and vastus lateralis averaged maximal EMG). The authors argued that, given limited flexors' strength, the extensors could not increase their activation as to maintain the zero-net torque in the joint. This argues against the usefulness of the paradigm for lower limb training.

However, we believe that the understanding of the underlying processes of the co-contraction training are still elusive, and, for this reason, the results might be limited. First, despite the supposed simplicity of the paradigm, one can question the feasibility of an instruction that requires large effort without motion. Co-contraction is an uncommon activity to be performed voluntarily. In such paradigm, visual control of movement or demonstrations are not as useful as they cannot identify what must be done as there is no observable kinematics. Then, if the suitability of the paradigm is wanted, one must, at least, offer multiple sessions to favor familiarization/practice.

A second issue is the potential variability between individuals in their co-contraction performance. Previous studies showed variable contributions of muscles groups during submaximal and maximal contraction tasks within and between-participants, given anatomical differences and control strategies [12–14]. 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 [6,9,15]). Even when joints spanned by many muscle groups are considered, the traditional emphasis in average values preclude consideration of how different individuals are stimulated within and between sessions.

Therefore, it is warranted to characterize how the co-contraction training stimulates the lower limbs of different participants through repeated sessions bearing in mind the range of possibilities that this training encompasses. This characterization is worthwhile; such range will define, through EMG behavior, the training efficiency [16]. In the present paper we characterize the co-contraction training of knee extensors and flexors, show its stimulus on the EMG activity, and investigate the variability between-/within-participants in the patterns of average and individual EMG activity. Specifically, this study elucidates (a) the overall muscle recruitment over the co-contraction training series (the demands of the co-contraction training); (b) the muscle recruitment behavior of knee flexors and extensors over a set of co-contractions; and (c) the intra/inter-individual variability on EMG magnitude between muscles in the same muscle group during the co-contraction training.

METHODS

Participants

Ten active male young adults (26.2±2.39 years of age; 82.9±10.27 kg; 1.76±0.05 m) with a minimum of one semester practicing physical exercises at least three times a week (range: [11 months to 11 years]) participated in this study. No participants reported orthopedic injuries in the previous six months or health problems that could affect performance. The local ethics committee approved all procedures (CAAE number: 199009.2.0000.5659).

Experimental Approach

All procedures below were the same for the first and second days (five days later).

Maximum isometric voluntary contraction (MIVC)

The first leg to be tested was chosen randomly between participants. 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 strongly 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). After 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, 2000 Hz) 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. [17] and Perotto et al. [18]. 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 192ms). 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 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

To understand whether training experience resolved some of the inter-individual variability, we first investigated the association between general outcomes of the isometric tests (peak torque of extensors, flexors, and their ratio) and training experience (in months) with EMG activity at the first day and the change from the first to the second day. Given the small sample size, we performed bootstrap covariance analyses that were later converted to Pearson's correlation measures (r).

To investigate the training stimulus consistency between participants on flexors and extensors, we performed a principal component analysis (PCA) between the average flexor and average extensor recruitment. Then, we noted the relative contribution of extensors and flexors to observe potential changes as a function of days and legs through a Hierarchical Linear Model (HLM) (see below).

To measure consistency in the muscle recruitment pattern over time, 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 [21] 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. Values below 0.9 demonstrate non-similar recruitment patterns.

To investigate a change in variability in the muscle recruitment pattern over time, 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 [21]. This was then utilized to analyze how the recruitment variability was modified as a function of days and legs through HLM (see below).

To investigate whether participants demonstrate similar recruitment patterns, 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. Then we examined the variability estimate and its bootstrapped confidence interval (1000 iterations) to investigate change over time. We also calculated the normalized dot product between each pair of participants for each block, day, and leg to observe whether common patterns of muscle recruitment between participants occurred.

Whenever the HLM analysis was considered, we employed the following procedure. Considering that within-participants data could be clustered, we evaluated the necessity of performing a HLM [19] by considering the intra-class correlation (ICC) of the null-model. For all instances where the ICC was above 0.15 and below 0.9 (indicating both within and between-participant variance to be explained) [20], 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 Supplementary Files).

RESULTS

Strength, Training Experience and EMG Activity Association

The associations between strength and experience measures with EMG outcome are reported in Table 1. As observed, the average muscle recruitment on the first day showed a negative correlation (r=-0.50 for the right leg) with flexor peak power and a positive correlation (r=0.49 and 0.59 for right and left legs, respectively) with training experience.

Table 1. Pearson's correlation between average muscle recruitment (first day and the change from first to second day) and strength and training experience variables.

	Right Leg		Left Leg	
	EMG_1	ΔEMG	EMG_1	ΔEMG
PT Extensors	-0.45	-0.08	-0.44	-0.12
PT Flexors	-0.50*	-0.20	-0.37	-0.02
Ratio F/E	-0.24	-0.19	-0.18	0.12
Training	0.49*	-0.04	0.59*	0.06

PT: Peak Torque; F/E: flexors/ extensors; * significant values at $p < .05$

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 (R^2=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 an increase of 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.

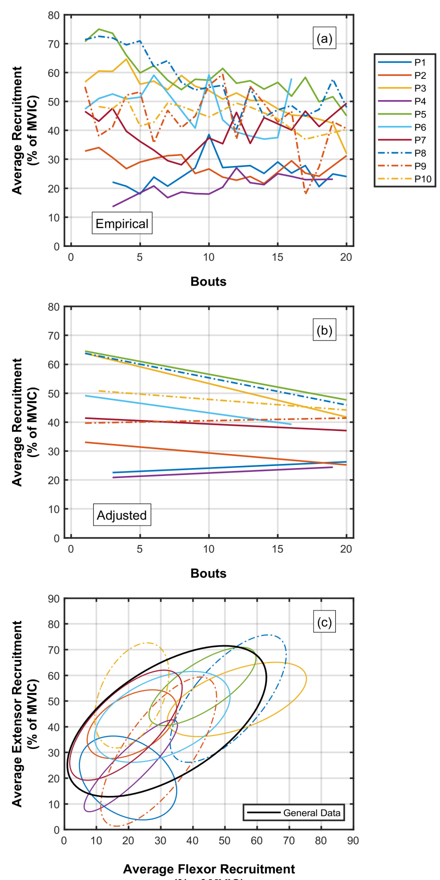

Figure 1. (a) Average muscle recruitment of each participant, for each of the twenty bouts during the first day; (b) Adjusted average muscle recruitment of each participant, for each of the twenty bouts during the first day; (c) Knee flexors and extensor mean recruitment relation, for each of the twenty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

Consistency Between Flexors-Extensors

The relation between flexor and extensor recruitment (through the PCA analysis) accounted for ~86.57% of the variance (see Supplementary File) (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).

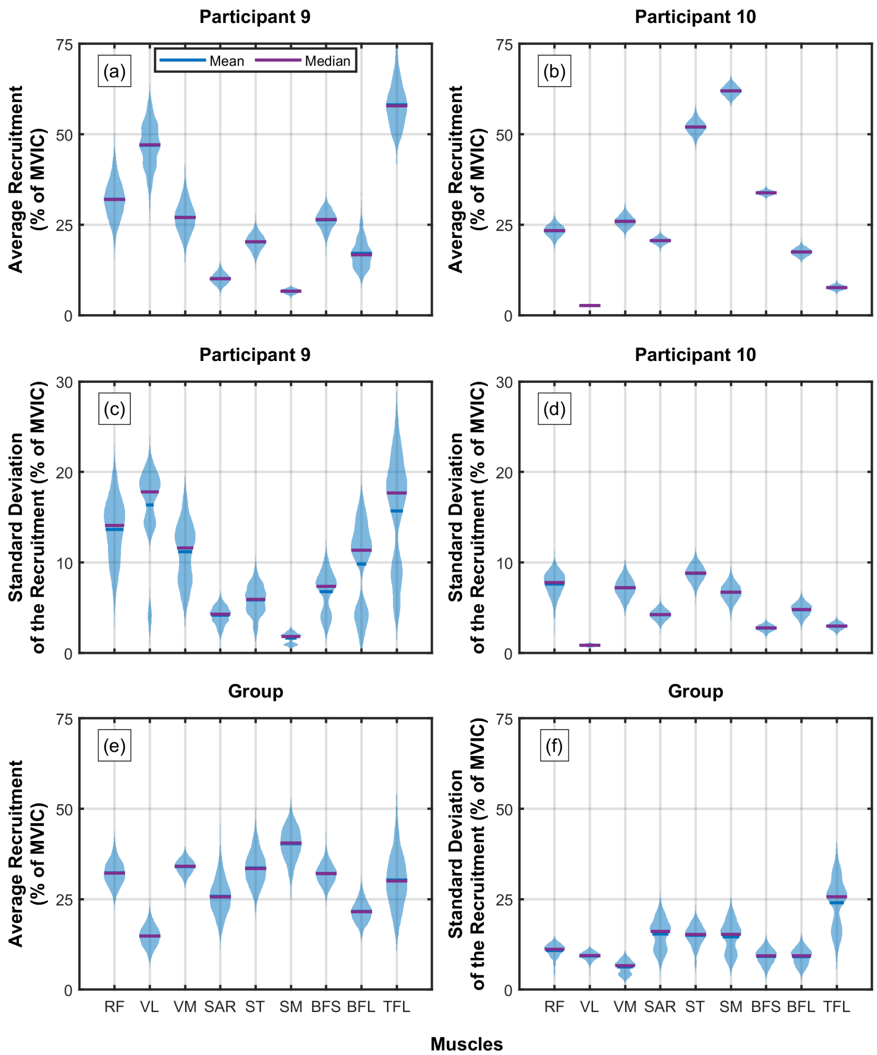

Figure 2. (a and b) Participant's 9 and 10 bootstrapped distributions of the average muscle recruitment, with the mean (blue) and median (purple) values, for all muscles captured during all repetitions of both legs and days; (c and d) Participant's 9 and 10 bootstrapped distribution of the muscular standard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

Regarding consistency in the average muscle recruitment pattern (see Figure 3), in 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.

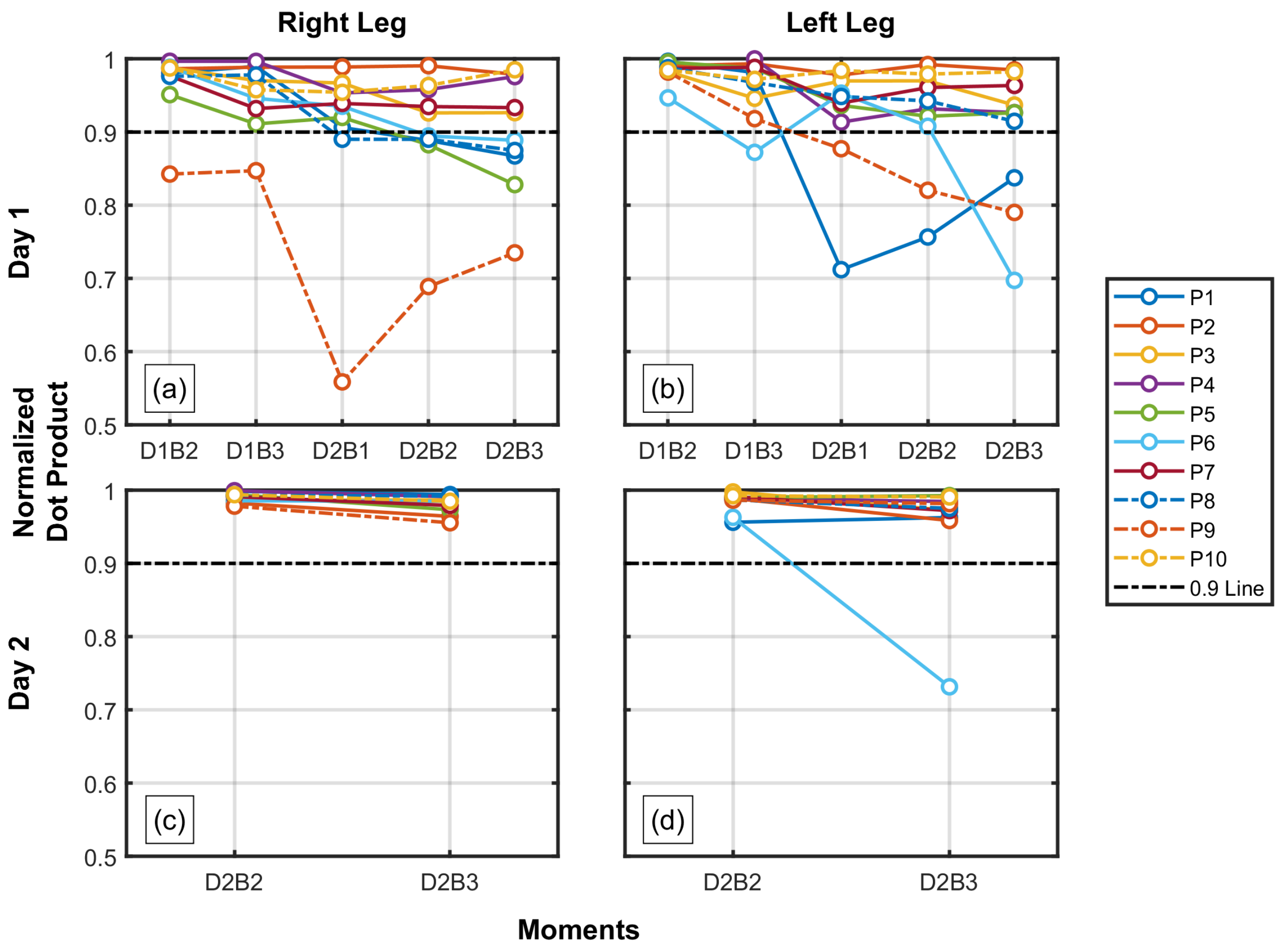

Figure 3. Participants muscle recruitment correlation coefficient behavior between day-one block-one and the following blocks of bouts of day one and two, for the right (a) and the left leg (b); Participants muscle recruitment pattern's correlation coefficient behavior between day-two, block one and 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.

Consistency Between Individual Muscles: Within Participant Variability

Decreases in muscle recruitment variability are possible if participants found efficient ways to perform the training. However, they might maintain the average recruitment while varying largely over trials. Using the radius of the 9-dimensional circle formed of all repetitions of each moment as a measure of within-participant variability, we investigated this possibility. 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. Using the between-participant radius of the 9-dimensional circle, 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.

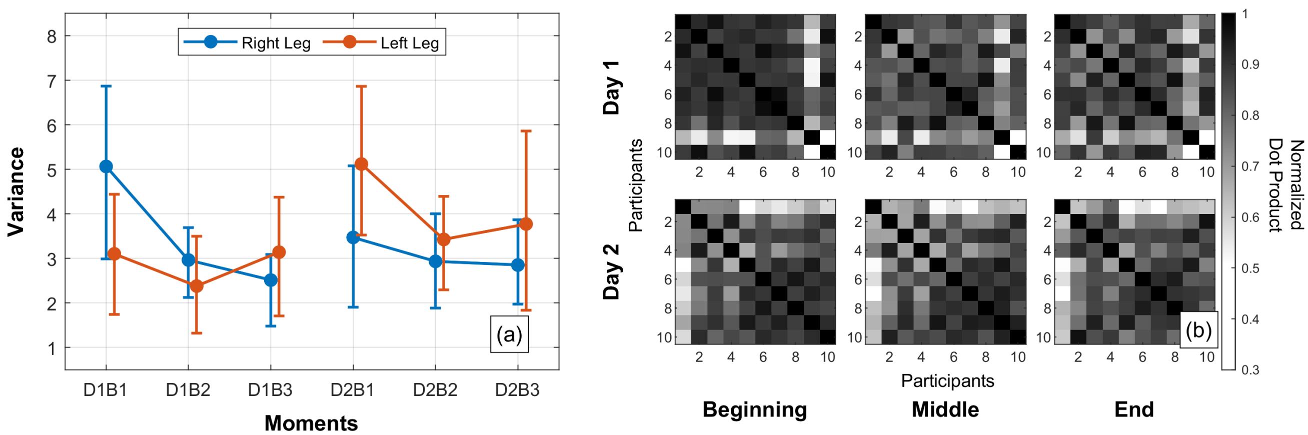

Figure 4. (a) Mean and confidence interval of the muscular recruitment variability between-individuals, for each of the blocks of bouts, for both days and legs; (b) Normalized dot product of muscular recruitment patterns between each pair of individuals, for each day and block of bouts. D1B1: Day one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

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 the 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 characterize the co-contraction training of the knee flexors and extensors through analyses of overall muscle recruitment, and between-/within-participant analyses of individual and group muscle through repetitions, days, and limbs. Our findings are that the training stimuli knee flexors and extensors with a considerable degree of activation and a high improvement rate through session. The flexor/extensor ratio is similar between participants while overall magnitude and muscle pattern recruitment is individual. Notably, however, is the large variability among individuals and the accommodation that might occur over bouts and days of practice.

The average muscle recruitment in our study was 36% of MIVC. This value is lower than other co-contraction studies with upper limbs (48 to 78% [8,9,22]) and conventional training paradigms (>36% [23–25]). However, this is higher than Maeo and Kanehisa [11] study in lower limbs (~32%). The co-contraction training is unusual and might induce, at least initially, less recruitment compared to other strength training paradigms. Consequently, perhaps, we found a general "practice" effect of 7% on muscle recruitment after a single practice session. This corroborates Maeo et al. [15] 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 would lead to increased muscle recruitment and, potentially, strength adaptations [6,9,10].

An 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 [26]. 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, increase their recruitment over repetitions–another positive compensation that requires no external intervention.

In general, we also found that the activation pattern observed correlated positively with training experience. This means that earlier practice in strength training might support the application of the method. If the observed correlation can be generalized, one would expect even lower EMG for inexperienced/sedentary individuals. An unexpected finding was that those who showed larger flexor torques in the isometric test were the ones who had most difficulty in showing large EMG activation during the co-contraction repetitions–a finding that challenges Maeo and Kanehisa [11] arguments. One argument is that there is limited generalization from one condition (isometric force) to the other (co-contraction). The former requires maximum inhibition of antagonists for large torque outcome while the latter requires an organized co-activation of all muscle in consonance to *decrease* torque outcome to its minimum. The small sample size of the present study forbids further speculation.

Within-participant changes in muscle recruitment demonstrate flexibility to accommodate different task demands (see [21,33]). Participants who changed their patterns (Figure 3) cannot be differentiated by their initial overall EMG recruitment level (P1: 11%, P6: 56%, P9: 31%) and, thus, also cannot be differentiated in terms of strength level or training experience. These changes in muscle recruitment patterns can refer to processes 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 [34]). The fact that less changes were observed in the second day demonstrates a more functional muscle recruitment pattern (see [35,36] for how myoelectric activity changes improve performance). That is, participants might have found a way to increase overall muscle recruitment with a "better" muscle recruitment pattern. It is interesting that these changes occurred without any concurrent feedback for participants.

How individuals vary while practicing is also important for coaches to understand whether the stimulus is consistent over repetitions and sessions. The untouched within-participant variability can mean different things depending on the magnitude of variation per participant. If large variability is observed, it can speak to the continuity of search for more stable recruitment patterns or even to strategies to dissipate fatigue between muscles [37,38]. If small variability is observed, it might refer to a stabilized (or even rigid) movement pattern [34]. In our data, initial variability had no relation to initial overall EMG recruitment (r = -0.12; p = .744) or changes in the EMG overall recruitment (r = -0.07; p = .838). Thus, this within-subject variability might reflect inherent variability of the system.

Despite the consensus in the literature of motor behavior on between-participants "motor styles" in a range of tasks [27], comparisons between exercises and training protocols largely ignore how participants vary in their responses (see also [28–30]). Despite the work of specific laboratories [31,32], we have difficulty finding studies that evaluate how the same participant responds differently over time, and how different participants differ under the same paradigm. 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 [12–14]. We found that the variability between them did not change (individuals were as different at the beginning as they were at the end of practice). Interestingly, we also failed to find robust "clustering" of muscle recruitment patterns between participants (Figure 4.b).

A major factor allowing emergence of within and between-participant variability is the task. Pacheco and Newell [39] explain that when tasks are redundant, participants exploit the potential solutions to accommodate their own intrinsic tendencies. 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 would make the task more constraining. However, through joint torque compensations (and consequently muscle recruitment), participants can also vary in these leading to different stimuli in the same task.

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 by 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 necessarily a bad feature.

Thus, contrary to what was pointed out in the single previous study in lower limbs [11], not only the training might be useful for targeted lower limb muscles but might expand muscles spanning other joints. Maeo and Kanehisa [11] considered that a limited muscle activation would occur given the common imbalance between knee flexors and extensors. Their view might be simplistic to understand how the motor system is able to accommodate new demands. When there is a multitude of muscles (mono and biarticular) involved in a given joint, large forces of a given muscle can be opposed (in an isometric co-contraction) through joints and muscles. Indeed, our findings show that not only individuals do that, but also, they do it differently. We believe that the exploitation of this abundance of motor solutions [40] should be always kept in mind when evaluating training paradigms.

We acknowledge limitations in our study. Despite the consistent compensation between flexors and extensors, muscles related to other joints might participate in the exercise, which we did not measure. 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. The between-individual variability is, also, a point that must be further investigated to understand whether training paradigms "*reinforce*" intrinsic coordination tendencies favoring asymmetries in muscle recruitment.

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