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ORIGINAL ARTICLE

A below-knee compression garment reduces fatigue-induced strength loss but not knee joint position sense errors

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Abstract

Purpose We examined the possibility that wearing a below-knee compression garment (CG) reduces fatigue-induced strength loss and joint position sense (JPS) errors in healthy adults.

Methods Subjects ($n = 24$, age = 25.5 ± 4 years) were allocated to either one of the treatment groups that performed 100 maximal isokinetic eccentric contractions at $30^{\circ -1}$ with the right-dominant knee extensors: (1) with (EXPCG) or (2) without CG (EXP) or to (3) a control group (CONCG*:* CG, no exercise). Changes in JPS errors, and maximal voluntary isometric contraction (MVIC) torque were measured immediately post-, 24 h post-, and 1 week post-intervention in each leg. All testing was done without the CG.

Results CG afforded no protection against JPS errors. Mixed analysis of variance (ANOVA) revealed that absolute JPS errors increased post-intervention in EXPCG and EXP not only in the right-exercised (52%, $p = 0.013$; 57%, $p = 0.007$, respectively) but also in the left non-exercised (55%, $p = 0.001$; 58%, $p = 0.040$, respectively) leg. Subjects tended to underestimate the target position more in the flexed vs. extended knee positions (75–61°: − 4.6 ± 3.6°, 60–50°: − 4.2 ± 4.3°, 50–25°: − 2.9 ± 4.2°), irrespective of group and time. Moreover, MVIC decreased in EXP but not in EXPCG and CONCG at immediately post-intervention ($p = 0.026$, $d = 0.52$) and 24 h post-intervention ($p = 0.013$, $d = 0.45$) compared to baseline.

Conclusion Altogether, a below-knee CG reduced fatigue-induced strength loss at 80° knee joint position but not JPS errors in healthy younger adults.

Keywords Isokinetic exercise · Eccentric contractions · Proprioception · Target-matching · Healthy

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János Négyesi and Li Yin Zhang contributed equally to this work.

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Abbreviations

ANOVA	Analysis of variance
CG	Compression garment
CONCG	Control group, receiving CG
EXPCG	Treatment group #1, performing isokinetic training with below-knee CG
EXP	Treatment group #2, performing isokinetic training without below-knee CG
JPS	Joint position sense
M	Peak torque
MVIC	Maximal voluntary isometric contraction
$MVIC_{60}$	MVIC test trials at 60°
$MVIC_{80}$	MVIC test trials at 80°
ROM	Range of motion
SD	Standard deviation

Introduction

Compression garments (CGs) have the potential to reduce the deleterious effects of fatigue on joint position sense (JPS) in healthy adults (Ghai et al. 2018; Miyamoto et al. 2011; Van Tiggelen et al. 2008a, b). Results, however, are inconsistent concerning how CGs affect knee JPS, the perceived sense of knee joint position and joint movement per se (Friden et al. 2001). For instance, some studies aimed to determine the effects of compression during exercise on JPS (Miyamoto et al. 2011), while others applied CGs only during the testing protocol (Van Tiggelen et al. 2008a, b). It is also possible that the conflicting data between studies are related to the location of where along the leg CG modulates afferent input. While above-knee CG failed to reduce passive (Negyesi et al. 2018) or active (Zhang et al. 2019) target-matching errors, CGs applied over the knee joint can improve JPS by reducing inter-trial variability (Zhang et al. 2019). Such favorable effects may be related to an augmented sense of movement due to skin stretching when CG covers the knee (Collins and Prochazka 1996). Yet there is also evidence for reductions in absolute repositioning error when the CG was placed below the knee (Zhang et al. 2019). Athletes and patients would prefer to place CGs below the knee because over-knee CGs can limit knee range of motion (ROM) and mobility (Lien et al. 2014).

Isokinetic contractions can activate and train muscles through the entire joint ROM at a pre-set and constant speed but the way exercise is executed can affect the training effects. Some but not all (Marks and Quinney 1993) experimental studies found that fatigue induced by isokinetic exercise affects active knee JPS in healthy older (Lattanzio et al. 1997; Ribeiro et al. 2007) and younger adults (Miura et al. 2004). Although concentric compared with eccentric contractions can induce more and longer lasting fatigue (*F*orce/torque loss) (Hortobagyi et al. 1996; Molinari et al. 2006), eccentric exercise can affect presynaptic inhibition of the Ia afferents (Vangsgaard et al. 2013), hence proprioception, especially when a CG is applied to modulate Ia activation. Eccentric exercise is, therefore, a reasonable choice to manipulate the effects of CG on force/torque loss and JPS. However, it is difficult to assess changes in JPS if the target-matching task is simple and JPS error is low at baseline. While not entirely clear, it seems that kinesthetic movement reproduction (Marini et al. 2018), which implies knowledge of the starting position and movement path for accuracy, as a proxy for JPS might be more sensitive than target matching tasks with constant initial knee angles (Ghai et al. 2018; Negyesi et al. 2018) to determine the effects of interventions and CGs on JPS in healthy humans.

Although previous studies demonstrated that (1) isokinetic exercise-induced fatigue reduces strength (Arora et al. 2015; Cadore et al. 2018) and (2) CGs may reduce fatigue effects (Ghai et al. 2018; Miyamoto et al. 2011; Van Tiggelen et al. 2008a, b), no previous study has examined yet the long-lasting effects of wearing a below-knee CG during a single bout of isokinetic exercise. Therefore, the aim of the present study was to determine if wearing a below-knee CG during isokinetic exercise would reduce strength loss and the deleterious effects of fatigue on JPS in healthy younger adults. We measured JPS using kinesthetic movement reproduction test immediately, 24 h, and 1 week after exercise. Additionally, we determined the changes in maximal voluntary isometric contraction (MVIC) torque on each leg at each time point. We used such a design to track muscle damage known to occur along this time course (Brown et al. 1997; Vaczi et al. 2011) and see its effects on JPS errors. Because CG without exercise could by itself affect JPS errors, we are particularly interested in a potential interaction between CG and exercise in relation to JPS error. We hypothesized that CG reduces the fatigue-induced deterioration in JPS. Moreover, JPS seems to be more accurate in more flexed knee positions (Negyesi et al. 2018) probably due to the greater background Ia discharge and feedback in this more stretched quadriceps position. It is, however, also possible that the short path and time from the starting position of 90° required participants to explore the target in a narrower range, reducing the probability for error. We, therefore, hypothesized that in line with our previous data, target angle affects JPS accuracy so that greater JPS errors can be found in more extended knee joint positions, irrespective of ROM.

Unilateral exhaustive exercise can affect the neuromuscular performance of not only the exercised (Arora et al. 2015; Cadore et al. 2018; Hortobagyi et al. 1996) but also the resting, contralateral leg (Halperin et al. 2014; Kawamoto et al. 2014; Martin and Rattey 2007). While JPS is an integral element of balance performance, unilateral fatigue effects have been inconsistent concerning static and dynamic balance performance in the non-exercised leg (Arora et al. 2015; Paillard et al. 2010). Perhaps the inconsistencies are related to a lack of understanding of how and if at all unilateral fatigue affects JPS in the non-exercised leg. Therefore, we also examined the potential transfer effects of unilateral eccentric fatigue on JPS of the non-exercised leg. We hypothesized that unilateral fatigue would also increase JPS errors in the non-exercised leg but to a smaller extent than in the exercised leg without the CG protecting against the fatigue effects because the magnitude of sensory effects produced by the CG is too small vis-à-vis the magnitude of fatigue.

Materials and methods

Participants

Sample size calculations (G*Power 3.1.7 Faul et al. 2007) for position sense were based on a previous study (Romero-Franco and Jimenez-Reyes 2017) which determined the effects of a fatigue protocol on the vertical jump and knee joint position sense of sprinters. Power analysis for repeated measures analysis of variance (ANOVA) indicated a total sample size of 24, assuming type I error of 0.05 and power of 0.80.

Based on the power analysis, 24 strongly right-side dominant healthy adults were enrolled in the study (age = 25.5 ± 4 years, range 18–34 years; height = 1.68 ± 0.1 m; mass = 63.0 ± 13.0 kg; 12 female). Because side-dominance affects JPS (Galamb et al. 2018), participants were strongly right hand (Oldfield 1971) and right leg (van Melick et al. 2017) dominant. We included individuals with high levels of physical activity to be able to tolerate high eccentric loads. Exclusion criteria: past or current fracture or muscle injuries, knee or ankle surgery in the lower extremities, and the use of drugs known to affect the central nervous system, equilibrium or muscle strength. After giving both verbal and written explanation of the experimental protocol, all participants signed an informed consent prior to the start of the experiments that was executed in accordance with the Declaration of Helsinki. The study was carried out in accordance with the recommendations of the University Medical Ethical Committee.

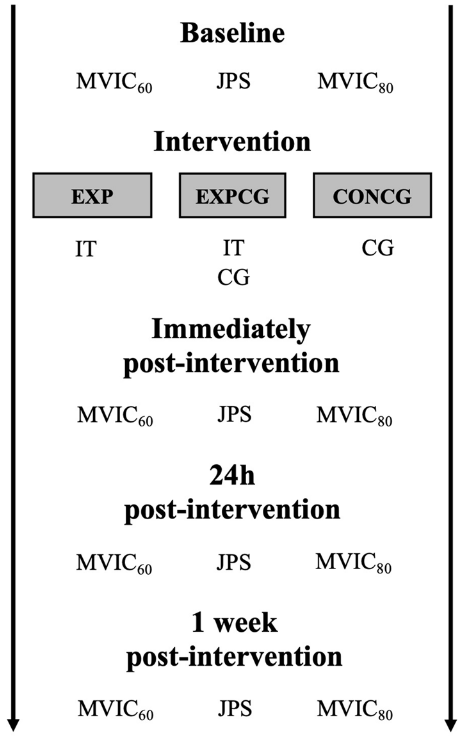

Fig. 1 Experimental design. Participants were randomly allocated in equal numbers to either a treatment group (1) with (EXPCG) or (2) without (EXP) a below-knee compression garment (CG) or 3) a control group (CONCG) that will not receive isokinetic training but a below-knee CG. Subjects visited the laboratory again 24 h post-, and 1 week post-intervention. JPS joint position sense, *IT* isokinetic training, $MVIC_{60}$ maximal voluntary contraction test trials at 60°, $MVIC_{80}$ maximal voluntary contraction test trials at 80°

Experimental procedures

Participants visited the laboratory three times (Fig. 1). Visit 1 consisted of the intervention with baseline and immediately post-intervention tests, while visits 2 (24 h post-intervention) and 3 (1 week post-intervention) consisted of testing only (see "Testing protocols"). Participants were randomly allocated to one of the treatment groups (1) with (EXPCG) or (2) without (EXP) a below-knee CG (D&M Co., Tokyo, Japan) or (3) a control group (CONCG) that did not perform the exercise but wore a below-knee CG. EXPCG and EXP performed 100 maximal isokinetic eccentric contractions with the extensors of the right-dominant leg at 30°/s. EXPCG wore a below-knee CG, extending between the superior aspect of the tibial tuberosity and the proximal two-thirds of the tibial shaft during the isokinetic exercise. CONCG also wore CG for the period of time that was required to perform the isokinetic exercise and sat quietly on the seat of the dynamometer (Cybex, division of Lumex, Inc., Ronkonkoma, New York, USA). EXPCG and *CON*CG wore the same best fitting CG of the three available sizes during the intervention. All testing was done without the CG.

Testing protocols

Kinesthetic movement reproduction In each group, participants carried out a kinesthetic movement reproduction task with the knee joint of each leg in a randomized order. Proprioception measurements were performed using the above-mentioned isokinetic Cybex NORM dynamometer. Subjects were blindfolded to limit the sensory feedback during the task only to proprioception. After a standardized warm-up, subjects were seated in the dynamometer chair in an upright position. One leg hung freely over the edge of the chair and the other leg was fixed to the attached free-moving arm, with a flexion angle of approximately 90°. After a test trial that was performed to familiarize the participant with the procedure, data collection was started. Before beginning the test, participants were instructed to focus on the leg position.

The involved leg was then passively moved with a velocity of 4°/s toward the target angle specified by the protocol. As soon as the attached free-moving arm reached the target angle, it stopped and held this position for 5 s, and then passively moved back to the initial starting position. Subjects were asked to actively match target positions that have location not fixed in space but that were passively shown trough movements of the same length (ROM: 32°, 24° and 16°) in a randomized order. Figure 2 shows the five experimental trials, indicating the four phases which constituted each trial. The 5 trials were performed with each ROM for each leg. To maintain attentional alert, after each set participants counted backwards by seven, starting from a two-digit number given by the experimenter.

Maximal voluntary isometric contraction (MVIC) torque The maximal voluntary isometric contraction (MVIC) tests were performed with the above-mentioned dynamometer. Subjects were seated on the dynamometer's padded seat, as previously described for measurement of kinesthetic movement reproduction test. First, subjects performed three MVIC trials at 60° ($MVIC_{60}$) and 80° ($MVIC_{80}$) (0° = full extension) with their knee extensors. Subjects were instructed to generate moment gradually and to reach maximal isometric moment in each of the three trials. Peak torques during isometric MVICs (M_{MVIC60}, M_{MVIC80}) were determined offline from the torque–time curves and were applied for statistical analysis. The subjects were allowed to follow the torque curves on the computer screen for visual feedback. In addi-

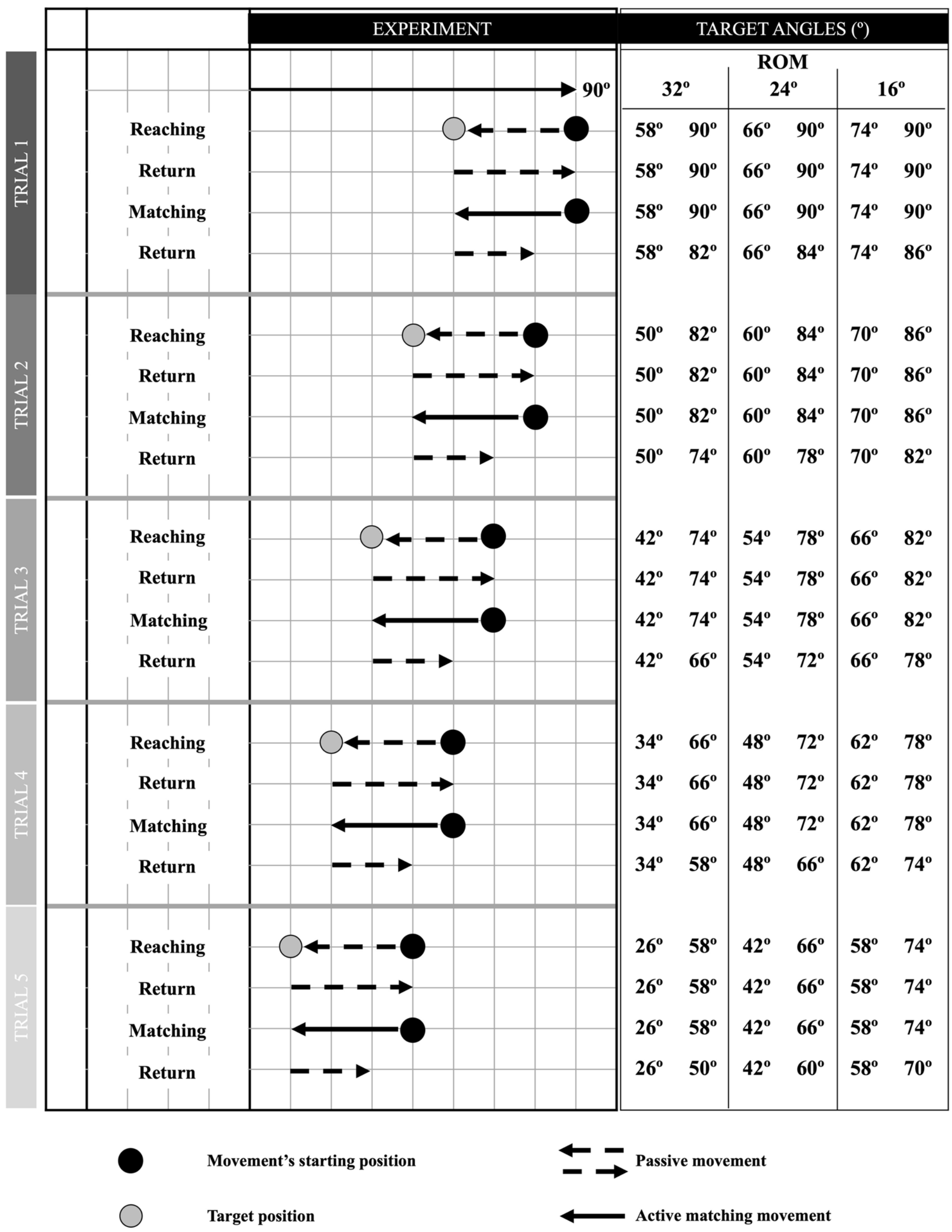

Fig. 2 Kinesthetic movement reproduction (adopted and edited from Marini et al. 2018). The included leg was passively moved with a velocity of 4°/s toward the target position specified by the protocol. As soon as the attached free-moving arm reaches the target angle, it stopped and held this position for 5 s. After the leg was released, it was passively brought back to the movement's starting position. Subjects were asked to actively match target positions that have a location not fixed in space but that were passively shown through movements of the same length (range of motion, ROM: 32°, 24° and 16°) in a randomized order

tion, they were given standardized verbal encouragement during the maximal contractions. To reduce inter-subject variability, data were normalized to body-weight and were applied for statistical analysis.

Isokinetic eccentric exercise

EXPCG and EXP performed 100 continuous maximal voluntary eccentric activations with the knee extensors of the dominant leg at 30°/s between 30° and 90°. The subjects were positioned as previously described for the measurement of kinesthetic movement reproduction test. The activations were performed as 10 sets of 10 eccentric contractions with 10 s of rest allowed between each sets. The subjects were encouraged to attain the highest score, which was aided by the instantaneous visual display of the peak torque curves on the computer monitor. Verbal feedback was also given to elicit maximal effort.

Data analyses

Kinesthetic movement reproduction

JPS was evaluated using three types of error: (1) absolute error, i.e. the measure of the magnitude of the error, without directional bias; (2) constant error, i.e. the measure of the deviation from the target with directional bias and (3) variable error, i.e. the measure of the consistency in performance, determined as the standard deviation from the mean of the relative errors. Besides absolute repositioning error, evaluating variable and constant errors might provide a different information on the integrity of the sensorimotor system by reflecting how accurately the target is represented in the nervous system (Rossetti et al. 1994; Vafadar et al. 2015).

In the present study, any deviation from the target position, discounting direction, was defined as the absolute position error:

$$E_{\text{absolute}} = |X_{\text{participant}} - X_{\text{target}}| \quad (1)$$

For constant error, the difference between reproduced and actual target angle was used, considering the direction of the error:

$$E_{\text{constant}} = (X_{\text{participant}} - X_{\text{target}}) \quad (2)$$

The variable error was calculated as the overall standard deviation (*SD*) of constant error from 5–5 trials, considering the target ROM:

$$E_{\text{variable}} = \sqrt{\sum \left(X_{\text{participant}} - E_{\text{constant}}\right)}^2 \quad (3)$$

Statistical analyses

The analyses were performed using SPSS Statistics Package (version 22.0, SPSS Inc., Chicago, IL). Variables were normally distributed, measured by Shapiro–Wilk's test of normality and visual inspection of their histograms. To statistically investigate the effect of a below-knee CG after the unilateral isokinetic exercise-induced fatigue training in each type (absolute, constant and variable errors) of kinesthetic movement reproduction error (JPS, the dependent measure), a group (EXPCG, EXP, CONCG) × time (baseline, immediately post-intervention, 24 h post-intervention, 1 week post-intervention) × ROM (32°, 24°, 16°) × leg (right-exercised, left not-exercised) mixed analysis of variance (ANOVA) and planned post hoc tests with Bonferroni correction for multiple comparisons were performed. To detect if the level of target angles may influence JPS accuracy, irrespective of ROM, a group (EXPCG, EXP, CONCG) × time (baseline, immediately post-intervention, 24 h post-intervention, 1 week post-intervention) x target level (75–61°, 60–50°, 50–25°) × leg (right-exercised, left not-exercised) mixed ANOVA with post hoc tests were conducted. Lastly, to investigate the changes in MVIC torque (dependent variables: M_{MVIC60}, M_{MVIC80}) in response to the unilateral isokinetic training, a group (EXPCG, EXP, CONCG) × time (baseline, immediately post-intervention, 24 h post-intervention, 1 week post-intervention) × leg (right-exercised, left not-exercised) mixed ANOVA was performed. Compound symmetry was evaluated with the Mauchly's test and Greenhouse–Geisser correction was used when data violated the assumption of sphericity, so that when the Epsilon was less than 0.75 for Mauchly's test of sphericity, we used the Greenhouse–Geisser-corrected value and the Huynh–Feldt-corrected value for epsilon greater than 0.75. Complementary post hoc analyses (paired samples *t* tests) were used when indicated. Cohen's effect size, *d*, was also computed as appropriate. Additionally, effect sizes of the independent variables were expressed using partial eta squared (η_p^2) (Peat et al. 2008). To determine if changes in kinesthetic movement reproduction were associated with changes in MVIC torque, Pearson's correlations were computed. Statistical significance was set at $p < 0.05$.

Results

Kinesthetic movement reproduction (*S1_Data_*JPS)

The analysis of absolute, constant and variable JPS errors (Table 1) performed by mixed ANOVA showed a main effect of time ($F_{3,63} = 11.5$, $p < 0.001$, $\eta_p^2 = 0.35$, $F_{3,63} = 8.1$, $p = 0.001$, $\eta_p^2 = 0.28$, $F_{3,63} = 3.9$, $p = 0.017$, $\eta_p^2 = 0.16$,

Table 1 Effects of isokinetic eccentric exercise on kinesthetic movement reproduction in each group, time point, leg, and range of motion

		EXPCG				EXP				CONCG			
		BL	PI	24 h	1w	BL	PI	24 h	1w	BL	PI	24 h	1w
Absolute error													
Right	32°	3.4 (1.4)	5.6 (1.8)	4.7 (1.4)	3.3 (1.1)	3.2 (1.4)	5.6 (2.0)	3.7 (1.9)	5.5 (2.4)	4.4 (2.2)	2.9 (1.2)	4.6 (1.7)	5.5 (3.5)
	24°	3.7 (2.2)	7.2 (0.6)	6.2 (3.1)	5.2 (1.6)	3.8 (1.6)	6.3 (2.7)	4.1 (1.8)	4.4 (2.5)	5.1 (3.6)	5.3 (2.3)	4.4 (3.3)	5.9 (4.0)
	16°	5.7 (3.6)	6.6 (0.8)	6.6 (2.7)	7.0 (3.2)	4.1 (1.4)	5.6 (4.1)	3.0 (1.5)	4.7 (2.8)	3.5 (2.2)	6.1 (3.0)	4.1 (1.6)	7.0 (4.2)
Left	32°	3.6 (1.7)	5.4 (2.5)	4.2 (1.4)	4.9 (1.6)	3.9 (1.7)	5.2 (3.0)	6.0 (3.8)	7.2 (4.7)	3.6 (0.3)	4.2 (1.8)	3.9 (0.9)	5.9 (2.8)
	24°	4.1 (1.6)	6.2 (2.1)	5.4 (1.9)	7.6 (1.9)	3.8 (1.3)	5.1 (2.0)	5.1 (1.5)	5.2 (2.6)	5.7 (3.6)	6.9 (4.1)	3.5 (1.5)	6.3 (3.9)
	16°	4.2 (2.0)	7.1 (2.7)	6.9 (1.9)	6.9 (1.6)	3.1 (1.2)	7.0 (3.8)	5.6 (1.7)	5.7 (2.6)	6.1 (3.4)	7.7 (3.4)	6.8 (3.2)	7.0 (5.7)
Constant error													
Right	32°	− 3.1 (2.9)	− 6.7 (2.1)	− 5.4 (2.0)	− 4.3 (2.1)	− 1.6 (2.1)	− 4.1 (4.5)	− 3.5 (4.0)	− 4.1 (5.8)	− 1.7 (3.3)	− 2.7 (1.7)	− 2.7 (3.3)	− 3.9 (5.3)
	24°	− 3.2 (2.5)	− 6.7 (1.2)	− 6.0 (3.3)	− 3.8 (2.7)	− 2.4 (2.3)	− 4.0 (5.3)	− 3.6 (4.9)	− 4.4 (6.1)	− 3.0 (5.6)	− 4.0 (3.3)	− 3.3 (4.3)	− 3.9 (5.9)
	16°	− 4.6 (4.8)	− 6.4 (0.9)	− 6.4 (3.0)	− 6.8 (3.4)	− 3.4 (2.0)	− 5.4 (4.4)	− 3.7 (2.7)	− 4.1 (3.3)	− 1.9 (3.7)	− 5.4 (3.9)	− 3.9 (1.7)	− 6.3 (3.2)
Left	32°	− 3.3 (1.2)	− 5.6 (2.2)	− 5.1 (1.0)	− 6.6 (1.7)	− 2.1 (3.9)	− 4.6 (4.5)	− 3.6 (3.5)	− 4.8 (7.1)	− 4.2 (3.9)	− 5.6 (3.2)	− 3.0 (2.2)	− 4.3 (5.4)
	24°	− 3.7 (1.6)	− 6.0 (2.5)	− 4.8 (2.1)	− 7.3 (2.1)	− 3.3 (4.7)	− 3.4 (2.8)	− 5.4 (6.5)	− 4.7 (7.8)	− 5.2 (4.1)	− 6.9 (4.1)	− 2.1 (2.3)	− 4.5 (5.8)
	16°	− 3.2 (2.6)	− 6.8 (2.9)	− 6.9 (1.9)	− 6.9 (1.6)	− 2.5 (1.8)	− 6.8 (4.0)	− 5.4 (2.1)	− 5.3 (3.2)	− 4.8 (4.8)	− 7.2 (4.2)	− 6.3 (3.5)	− 6.5 (6.3)
Variable error													
Right	32°	3.4 (1.4)	4.3 (1.3)	3.9 (1.5)	3.5 (1.2)	3.2 (1.2)	4.2 (1.8)	2.6 (1.0)	3.9 (1.8)	4.5 (1.9)	2.7 (1.3)	3.1 (1.4)	3.7 (1.2)
	24°	2.8 (1.0)	4.8 (1.4)	3.0 (1.5)	4.8 (0.7)	3.3 (1.4)	4.5 (1.8)	3.2 (1.3)	3.6 (1.5)	3.0 (1.1)	2.9 (0.9)	2.5 (1.4)	3.0 (1.8)
	16°	2.8 (1.1)	3.6 (1.4)	3.6 (0.4)	3.0 (0.7)	3.4 (1.1)	3.5 (1.8)	2.6 (1.8)	3.4 (2.0)	2.3 (0.9)	4.1 (2.1)	2.5 (1.0)	3.5 (1.1)
Left	32°	3.4 (1.4)	4.0 (1.9)	4.0 (1.5)	3.1 (0.6)	4.4 (2.0)	4.3 (1.7)	3.2 (1.6)	4.8 (1.9)	3.5 (0.7)	3.9 (1.2)	4.0 (1.5)	4.8 (2.1)
	24°	3.5 (1.3)	3.7 (1.4)	3.6 (0.3)	3.4 (1.6)	3.0 (0.8)	4.0 (2.1)	3.5 (1.8)	4.2 (1.7)	3.2 (1.3)	3.0 (1.3)	3.1 (1.1)	3.7 (1.4)
	16°	3.8 (1.9)	3.6 (2.1)	3.4 (0.7)	3.4 (1.1)	2.2 (0.8)	3.7 (1.3)	3.4 (1.3)	3.0 (1.6)	4.0 (1.6)	3.6 (0.8)	3.6 (1.5)	3.0 (2.1)

Values are mean (SD) of each position sense errors in degrees

EXPCG treatment group #1, performing isokinetic training with below-knee CG, EXP treatment group #2, performing isokinetic training without below-knee CG, *CON*CG control group, receiving CG, *BL* baseline, *PI* immediately post-intervention, *24 h* 24 h post-intervention, *1w* 1 week post-intervention respectively), ROM ($F_{2,42}=6.0$, $p=0.008$, $\eta_p^2=0.22$, $F_{2,42}=7.7$, $p=0.001$, $\eta_p^2=0.27$, $F_{2,42}=6.9$, $p=0.003$, $\eta_p^2=0.25$, respectively) and leg ($F_{1,21}=4.6$, $p=0.043$, $\eta_p^2=0.18$, $F_{1,21}=5.7$, $p=0.026$, $\eta_p^2=0.22$, $F_{1,21}=5.0$, $p=0.037$, $\eta_p^2=0.19$, respectively). In each repositioning error, immediately post-intervention values compared to baseline values significantly increased (absolute: 41%, constant: 72%, variable: 14%), but recovered by 24 h post-intervention, irrespective of group. Participants tended to perform the kinesthetic movement reproduction task more accurately and with lower variability with the exercised (4.9 ± 2.6°, 3.4 ± 1.5°, respectively) vs. non-exercised leg (5.5 ± 2.8°, 3.6 ± 1.5°, respectively), irrespective of group and time. There was also a time x leg x group interaction ($F_{6,63}=3.5$, $p=0.008$, $\eta_p^2=0.25$) with the post hoc analysis revealing that absolute JPS errors increased post-intervention in EXPCG and EXP not only in the right-exercised (52%, $p=0.013$, $d=1.07$; 57%, $p=0.007$, $d=0.91$; respectively) but also in the left non-exercised (55%, $p=0.001$, $d=1.06$; 58%, $p=0.040$, $d=0.90$; respectively) leg; however, it recovered only in the right leg in EXP 24 h post-intervention. CG alone in CONCG did not induce any changes in absolute JPS over time (Fig. 3). Furthermore, although we found less absolute repositioning error at 32° (4.6 ± 2.3°) as compared to 16° (5.7 ± 3.1°) ROM, variability of the errors was also greater at 32° (3.8 ± 1.5°) vs. 16° (3.3 ± 1.4°) ROM.

ANOVA with repeated measures on time, target angles, and leg revealed a main effect of target angles ($F_{2,42}=9.2$, $p=0.002$, $\eta_p^2=0.30$), time ($F_{3,63}=7.6$, $p=0.001$, $\eta_p^2=0.27$) and leg ($F_{1,21}=4.7$, $p=0.042$, $\eta_p^2=0.18$) in constant errors but no group x target angle interaction ($F_{4,42}=0.8$, $p=0.518$, $\eta_p^2=0.07$), suggesting that target angles did not affect JPS after exercise with or without CG. Nevertheless, post hoc analysis showed less constant JPS errors in the more extended vs. flexed positions (75–61°: − 4.6 ± 3.6°, 60–50°: − 4.2 ± 4.3°, 50–25°: − 2.9 ± 4.2°), irrespective of group and time (Fig. 4). Variable position errors showed a main effect of target angles ($F_{2,42}=10.0$, $p<0.001$, $\eta_p^2=0.32$), group ($F_{2,21}=40.7$, $p<0.001$, $\eta_p^2=0.80$) and leg ($F_{1,21}=24.8$, $p<0.001$, $\eta_p^2=0.54$) with larger variability in JPS errors when reaching at 60–50° (2.8 ± 3.4°) as compared to 75–61° (2.2 ± 4.1°, $p<0.001$, $d=0.16$) and 50–25° (2.1 ± 3.7°, $p<0.001$, $d=0.20$).

Maximal voluntary isometric contraction (MVIC) *torque* (*S2_Data_*MVIC)

Table 2 summarizes the effects of isokinetic eccentric exercise on maximal voluntary isometric strength in each group, time point, and leg. There was a main effect of group ($F_{2,21}=4.6$, $p=0.023$, $\eta_p^2=0.30$) and leg ($F_{1,21}=28.8$, $p<0.001$, $\eta_p^2=0.58$) in M_{MVIC60} with the post hoc analysis showing greater peak torques in the exercised (244.4 ± 68.1 N/kg%) vs. non-exercised (222.2 ± 57.3 N/kg%) leg, irrespective of group and time ($p<0.001$, $d=0.35$). On the other hand, M_{MVIC80} revealed

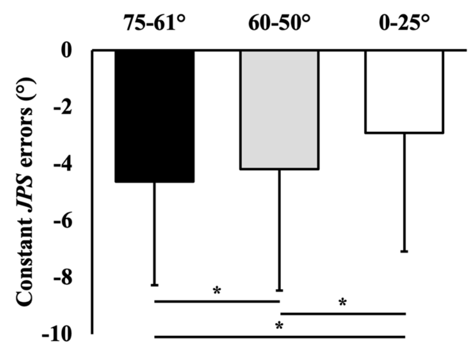

Fig. 4 Constant JPS errors. Participants had less constant JPS errors in more extended vs. flexed positions. *$p<0.05$. Vertical bars denote + 1SD

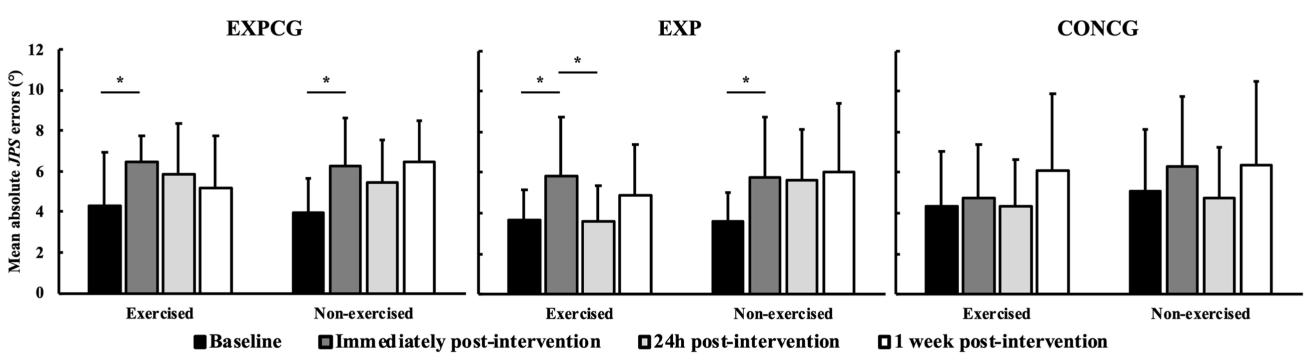

Fig. 3 Absolute JPS errors in each group in the exercised and non-exercised leg at different time points. Absolute JPS errors increased immediately post-intervention in EXPCG and EXP not only in the right-exercised but also in the left non-exercised leg. Baseline (black bar); immediately post-intervention (dark grey bar); 24 h post-intervention (light grey bar); 1 week post-intervention (white bar). EXPCG: treatment group #1, training + CG; EXP: treatment group #2, training only; *CON*CG: control group, only CG. *$p<0.05$. Vertical bars denote + 1*SD*

Table 2 Effects of isokinetic eccentric exercise on maximal voluntary isometric strength in each group, time point, and leg

	EXPCG				EXP				CONCG			
	BL	PI	24 h	1w	BL	PI	24 h	1w	BL	PI	24 h	1w
M_{MVIC60}												
Right	1.9 (0.5)	2.1 (0.7)	2.0 (0.6)	2.3 (6.1)	2.7 (0.8)	2.1 (0.4)	2.4 (0.9)	2.3 (0.4)	2.8 (0.4)	3.0 (0.6)	2.9 (0.6)	2.8 (0.7)
Left	1.7 (0.4)	2.2 (0.8)	2.0 (0.5)	2.0 (0.5)	2.2 (0.5)	2.2 (0.6)	2.1 (0.2)	2.2 (0.4)	2.5 (0.4)	2.7 (0.6)	2.6 (0.6)	2.6 (0.5)
M_{MVIC80}												
Right	2.4 (0.8)	2.6 (0.9)	2.6 (0.9)	3.0 (0.8)	3.4 (0.8)	3.2 (0.6)	2.9 (1.1)	3.0 (0.9)	3.1 (0.8)	3.2 (0.8)	3.3 (1.0)	3.2 (1.1)
Left	2.4 (0.9)	2.5 (1.0)	2.3 (0.8)	2.5 (0.8)	2.8 (0.6)	2.9 (0.7)	2.8 (0.7)	2.8 (0.6)	3.1 (0.8)	3.1 (0.8)	3.1 (0.9)	3.1 (0.9)

Values are mean (SD) of each position sense errors in degrees. Values are expressed as maximal torque/body-weight

EXPCG treatment group #1, performing isokinetic training with below-knee CG, EXP treatment group #2, performing isokinetic training without below-knee CG, *CON*CG control group, receiving CG, *BL* baseline, *PI* immediately post-intervention, *24 h* 24 h post-intervention; *1w* 1 week post-intervention, M_{MVIC60} maximal isometric torque at 60°, M_{MVIC80} maximal isometric torque at 80°

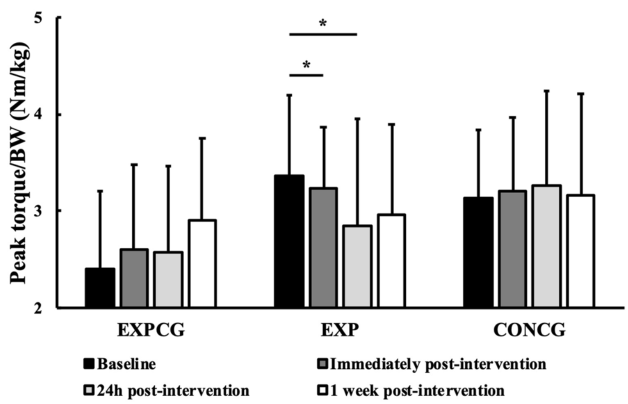

Fig. 5 The effect of interventions on body-weight normalized maximal voluntary isometric contraction (MVIC) torque of the right-exercised at 80° in each group and time points. Participants in EXP but not in EXPCG and CONCG had greater $MVIC_{80}$ values at baseline compared to immediately post-intervention and 24 h post-intervention. Baseline (black bar); immediately post-intervention (dark grey bar); 24 h post-intervention (light grey bar); 1 week post-intervention (white bar). $*p<0.05$. Vertical bars denote + 1SD

a main effect of leg ($F_{1,21}=10.3$, $p=0.004$, $\eta_p^2=0.33$) and also a group × time × leg interaction ($F_{6,63}=3.4$, $p=0.009$, $\eta_p^2=0.24$). Post hoc analysis revealed that participants in EXP but not in EXPCG and *CON*CG had smaller MVIC torque values in the exercised leg at immediately post-intervention (323.0 ± 63.7 N/kg%, $p=0.026$, $d=0.52$) and 24 h post-intervention (285.3 ± 109.6 N/kg%, $p=0.013$, $d=0.45$) compared to baseline (336.3 ± 84.2 N/kg%), suggesting that the below-knee CG used in the present study reduced the effects of fatigue, induced by the isokinetic eccentric exercise, on maximal voluntary torque (Fig. 5). However, decreased MVIC torque values in EXP did not correlate with changes in JPS errors ($p<0.05$).

Discussion

The aim of the present study was to determine if wearing a below-knee CG during isokinetic exercise would reduce strength loss and the deleterious effects of fatigue on JPS in healthy younger adults immediately, 24 h, and 1 week after exercise. CG failed to reduce the deleterious effects of fatigue on JPS. Absolute JPS errors increased immediately post-intervention in EXPCG and EXP not only in the right-exercised but also in the left non-exercised leg. In contrast to our hypothesis, participants had less constant JPS errors in more extended vs. flexed positions. Furthermore, JPS errors did not increase with the increase in ROM. In fact, subjects had less absolute repositioning error at 32° as compared to 16° ROM. Additionally, fatigue was demonstrated only in the EXP group, suggesting that the below-knee CG used in the present study compensated the fatigue effects on maximal voluntary torque in more flexed knee joint position.

While CG has the potential to modulate the activation of Ia afferents, it is possible that the speculated changes in presynaptic inhibition of the Ia afferents (Vangsgaard et al. 2013) induced by the eccentric exercise in the present study was so strong that it minimized beneficial effects of CG on JPS, if any.

Although participants exercised the right dominant leg, they tended to perform kinesthetic movement reproduction task more accurately and with lower variability with their right-exercised (4.9 ± 2.6°, 3.4 ± 1.5°, respectively) vs. left non-exercised leg (5.5 ± 2.8°, 3.6 ± 1.5°, respectively), irrespective of group and time. Although the differences in JPS errors were significant, they were minimal. Whether such minimal detectable differences have any physiological/functional importance is questionable. In addition, unilateral exercise increased absolute JPS errors immediately post-intervention in EXPCG and EXP not only in the right-exercised but also in the left non-exercised leg which is in line with some (Paillard et al. 2010) but not all (Arora et al. 2015) previous studies that aimed to detect the effect of unilateral fatigue exercise on proprioceptive balance performance of the contralateral leg. These contradictory data among studies can be due to the discrepancies in the duration and the intensity of the fatigue protocols. Specifically, it was shown that 10 sets of 50 repetitions of unilateral MVIC or neuromuscular electrical stimulation with 10% of M_{max} intensity (4 s activation, 2 s rest in each repetition) resulted in altered postural control in the contralateral leg (Paillard et al. 2010), while 15 MVIC with 30% of M_{max} intensity (16 s activation, 4 s rest in each repetition) failed to detect changes in non-exercised leg force-production (Arora et al. 2015). Nevertheless, in line with our hypothesis, unilateral exercise resulted in increased JPS errors but to a smaller extent in EXPCG with the CG as compared to EXP both in the exercised (52% vs. 57%) and non-exercised (55% vs. 58%) leg most probably due to the magnitude of sensory effects produced by the CG, which slightly protected against the fatigue effects.

While most previous studies used a constant initial position for target matching tasks, we used a kinesthetic movement reproduction task (Fig. 2) that implies knowledge of the starting position and movement's length for accuracy. This setup excludes the possibility that an increase in the ROM increases the cognitive difficulty of the task, resulting in greater JPS errors in more extended knee joint positions (Negyesi et al. 2018). Indeed, we found less absolute repositioning error at 32° (4.6 ± 2.3°) as compared to 16° (5.7 ± 3.1°) ROM, but the variability of the errors became greater at 32° (3.8 ± 1.5°) vs. 16° (3.3 ± 1.4°) ROM. This experimental protocol using isokinetic task, therefore, seems to have sufficiently eliminated the ROM effect on cognitive difficulty. We believe that the lower JPS errors in subjects' exercised vs. non-exercised leg were found due to our successful experimental set up so that subjects performed the target-matching task more accurately with their dominant as compared to non-dominant leg even after fatiguing exercise when the task was more difficult.

In contrast to the hypothesis, participants had less constant JPS errors in more extended vs. flexed positions (75–61°: − 4.6 ± 3.6°, 60–50°: − 4.2 ± 4.3°, 50–25°: − 2.9 ± 4.2°), which is in contrast with a previous study (Negyesi et al. 2018) showing less JPS errors at 60° compared to 30° and 45° of knee flexion with and without the application of an above-knee CG. It is possible that in this more flexed knee position compared with 30° and 45°, the quadriceps was more stretched, resulting in greater background Ia discharge and feedback, reducing the error. However, previous studies should have considered whether their results were due to the increase in ROM from a constant initial position so that the short path and time from the starting position of 90°–60° required participants to explore the target in a narrower range, reducing the probability for error. In the present study, however, our experimental setup prevented us from misinterpretation of the results, demonstrating less constant JPS errors in more extended vs. flexed positions, irrespective of ROM. Kinesthetic movement reproduction rather than proprioceptive identification of joint position, therefore, is more likely to be used in future studies that aim to investigate target matching accuracy.

Besides asymmetry in JPS accuracy, strongly right-side dominant subjects also had greater MVIC torque in the exercised (2.4 ± 0.7 Nm/kg) vs. non-exercised (2.2 ± 0.6 Nm/kg) leg, irrespective of group. The lack of group × time interaction indicates that exercise neither with nor without CG affected MVIC torque over time. This is in contrast with some (Busko et al. 2018) but not all (Guette et al. 2005) studies. People tend to use much more their dominant hand (Fugl-Meyer et al. 1982), such a relationship is less clear for the legs. Nevertheless, some previous studies (Tanaka et al. 1984; Zijdewind et al. 1990) demonstrated differences in fatigue resistance even between the dominant and non-dominant upper limb probably due to the morphological and physiological adaptations in muscle structure and function (Adam et al. 1998). Consistent with these data, the results of our study from strongly right-side dominant subjects support the idea that a preferential use of knee extensor muscles on one side leads to greater MVIC torque production in the dominant vs. non-dominant leg.

While previous studies demonstrated that (1) isokinetic exercise-induced fatigue reduces strength (Arora et al. 2015; Cadore et al. 2018), and (2) CGs may reduce fatigue effects (Ghai et al. 2018; Miyamoto et al. 2011; Van Tiggelen et al. 2008a, b), we also determined if fatigue effects were present in neuromuscular function and if CG reduces the fatigue-induced deleterious effects. In line with our expectations, participants only in EXP, who exercised without CG, had smaller MVIC torque values immediately post-intervention (3.2 ± 0.6 Nm/kg) and 24 h post-intervention (2.9 ± 1.1 Nm/kg) compared with MVIC torque values at baseline (3.4 ± 0.8 Nm/kg) at 80° knee angle. The underlying mechanism of how a CG can reduce muscle fatigue during exercise is straightforward; the pressure produced by the CG increases the intramuscular pressure, consequently decreasing the cross section of blood vessels and accelerating the blood flow (Ibegbuna et al. 2003; Maton et al. 2006). It has been, therefore, speculated that CGs can reduce venous stasis at rest and facilitate the venous return to the heart during exercise by increasing the efficacy of the muscle pump (Alimi et al. 1994; Raju et al. 1993).

The limitation of the study is the relatively low sample size. Although the power-analysis revealed that 24 subjects would be sufficient to detect changes in JPS between groups through time, increasing the sample size would possibly increase the statistical power. The interpretations of our results are based on significant but minimal differences in

JPS errors. It is unclear if such small effects are functionally relevant. Because the magnitude of differences in JPS errors between groups and other independent variables were similar to effects of 1–3 degrees after the application of external supports (Ghai et al. 2018; Negyesi et al. 2018; Tiggelen et al. 2008a, b; Van Tiggelen et al. 2008a, b; Zhang et al. 2019), or other experimental manipulations (Galamb et al. 2018), it is likely that our results are not due to measurement error. Moreover, in the present study, we were specifically interested in the effect of below-knee CG when applying during isokinetic training. However, adding one more group to the study, in which participants did not train or wear CG would have allowed us to understand JPS behavior more accurately across time.

Future studies need to solve the inconsistencies by separating the effects of compression from placebo (Mothes et al. 2017) through the detection of the physiological mechanisms underlying the effect of compression on target-matching behaviour. Using kinesthetic movement reproduction task rather than a proprioceptive identification of joint position is more favorable because this setup excludes the possibility that an increase in the ROM increases the cognitive difficulty of the task, resulting in greater JPS errors in more extended knee joint positions. Therefore, we strongly encourage researchers to use this experimental setup and also to analyze not only absolute but also constant and variable errors to clearly detect target-matching behavior. In the present study, we only determined the effect of a single bout of isokinetic eccentric exercise on kinesthetic movement reproduction and MVIC torque, *F*uture studies might therefore detect if an isokinetic exercise program lasting for weeks would have different outcomes than the results presented in this study.

Conclusions

In conclusion, JPS errors increased immediately after exercise, but recovered at 24 h post-intervention, irrespective of group. Additionally, absolute JPS errors increased immediately post-intervention in EXPCG and EXP not only in the right-exercised but also in the left non-exercised leg. Constant JPS errors were less in more extended vs. flexed positions and did not increase with the increase in ROM. Moreover, participants in EXP but not in EXPCG and CONCG had greater $MVIC_{80}$ values at baseline compared to immediately post-intervention and 24 h post-intervention, suggesting that the below-knee CG used in the present study compensated the fatigue effects on maximal voluntary torque in more flexed knee joint position. Our results add to the body of literature by detecting that below-knee CGs have the potential to reduce the effects of unilateral fatigue exercise on MVIC torque but afford no protection against JPS errors. This finding may help us better understand how the application of a CG during exercise can decrease the risk of musculoskeletal injuries during sport activities.

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Compliance with ethical standards

Conflict of interest All authors declare that they do not have any conflict of interest.

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