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Neuroscience Letters xxx (2005) xxx–xxx
Neuroscience Letters
www.elsevier.com/locate/neulet

A multi-joint lower-limb tracking-trajectory test for the assessment of motor coordination

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Received 4 March 2005; received in revised form 20 April 2005; accepted 20 April 2005

Abstract

This study aimed to determine whether a lower-limb trajectory-tracking task performed on a leg press machine, that is commonly adopted in both rehabilitation and resistance training settings, could yield reliable assessment of motor coordination in able-bodied individuals. Twenty-two female subjects allocated to two experimental groups were tested and retested after 48–72 h. Group A was fully familiarized with the experimental procedures before each test while group B received only verbal instructions. The unilateral coordination test consisted of target tracking during a simulated half squat including eccentric and concentric actions. In both groups, tracking error showed significant test-retest reliability with ICC values of 0.77–0.80 ($p < 0.05$). Significant group (A < B) and time (day 2 < day 1) main effects were found for tracking error, while there was no significant influence of action mode and dominance. Tracking error significantly decreased in the group A (∼15%) but not in the group B on retest. Action mode (eccentric versus concentric), side dominance and familiarization on day 1 had no effect on tracking error. However, movement control significantly improved at day 2, thus confirming the occurrence of short-term motor learning and the sensitivity of the present trajectory-tracking test. For the first time, a simple test for the assessment of motor coordination during multi-joint closed-kinetic chain action of lower limb muscles has been proposed. Its uniqueness is represented by the specificity for rehabilitation and resistance training settings. Further studies with larger sample groups (e.g., male subjects and patients) and including neurophysiological measurements are needed.

Keywords: Coordination; Leg press; Tracking ability; Motor learning

Trajectory-tracking tasks are commonly used in healthy individuals and in persons with movement disorders for quantitating movement control (i.e., motor coordination [17] or motor skill [15]) during a single joint movement, such as finger or elbow flexion-extension. This technique has proven useful to investigate the effect of age [7,19], gender [7], fatigue [15], training [2,6], and also central nervous system impairment [14] on tracking accuracy. Carey et al. [7] also demonstrated that in healthy subjects the nonpreferred (non-dominant) hand tracked more accurately than the preferred hand. Less information is however available on tracking control during the flexion compared to the extension phase of a test [7], i.e., during shortening (concentric) versus lengthening (eccentric) muscle actions.

The majority of the studies investigating tracking performance have focused on movements about a single joint of the upper extremities, whereas, to our knowledge, lower-limb trajectory-tracking task was considered only in one instance [6]. These authors examined the ability of one stroke patient to perform accurately controlled plantar flexion and dorsiflexion (open kinetic chain) movements with a single joint ankle test. Surprisingly, tracking ability during multi-joint closed-kinetic chain actions of the lower limb muscles has never been analysed to date, even if activities of daily living, that require the ability of movement control in addition to force control, are mostly performed in these conditions, particularly for the muscles involved in maintaining posture and balance. Consequently, it is reasonable to verify the feasibility

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0304-3940/$ – see front matter © 2005 Published by Elsevier Ireland Ltd.
doi:10.1016/j.neulet.2005.04.064

of a specific trajectory-tracking test involving the participation of the most important lower limb extensor (agonist) and flexor (antagonist) muscles.

The first aim of this study was to determine whether a lower-limb trajectory-tracking task performed on a commercially available horizontal leg press machine, that is commonly adopted in both rehabilitation and resistance training settings, could yield reliable assessment of motor coordination in able-bodied female individuals. To address this problem, we used a simple test-retest design and evaluated the basic properties of the trajectory-tracking task.

Based on previous research on tracking ability assessment, we also tested the following hypotheses: (i) the non-dominant lower limb would track more accurately than the dominant [7]; (ii) accuracy in the concentric phase of the movement (extension) would be higher than during the eccentric (flexion) phase; (iii) very short-term (warm-up before the first session) and short-term (second versus first session) learning effect over a limited number of trials would improve trajectory-tracking accuracy [9].

Twenty-two healthy and physically active female subjects volunteered to participate in this study. They gave written, informed consent before the experiment and the approval for the project was obtained from the Local Committee on Human Research (Schulthess Klinik, Zürich, Switzerland). The study was conducted according to the Declaration of Helsinki (last modified in 2000).

Participants were instructed to refrain from strenuous physical activity for 24 h prior to testing and to maintain normal exercise levels throughout the period of the experiment. They were randomly allocated to two experimental groups ($n = 11$ for both): group A (mean age ± S.D.: 28 ± 3 years; height: 169 ± 5 cm; mass: 58 ± 7 kg) and group B (age: 27 ± 3 years; height: 169 ± 5 cm; mass: 62 ± 10 kg). All subjects were tested and retested (mean interval between day 1 and day 2: 48–72 h) for tracking ability assessment on a commercially available horizontal leg press machine (Functional Squat System, Monitored Rehab Systems, Haarlem, The Netherlands), as detailed below. The movement considered is a ‘simulated’ one-leg half-squat, starting from a supine position, with the hip, knee and ankle joints flexed at ∼90°. The load (range 0–100 kg) is raised during the first phase by concomitant hip, knee and ankle extension (i.e., concentric contraction of the main lower limb extensor muscles) until the knee joint is fully extended. This is followed by the flexion phase, where the same (agonist) muscle groups are stretched (i.e., eccentric action) while the antagonist flexor muscles are coactivated during the entire half squat movement. Throughout this paper, the terms concentric and eccentric will be used instead of flexion and extension, respectively, and will refer to the action of the main hip (gluteus maximus), knee (quadriceps femoris) and ankle (triceps surae) extensor muscles. The machine is connected to a personal computer and a dedicated software provides real-time and off-line data analysis. Individuals from both groups completed a familiarization phase (duration: 5 min) before the coordination test, with group A (but not group B) also completing a standardised warm-up (duration: 15 min) in the two occasions (i.e., days 1 and 2), aimed at improving motor learning. All testing sessions were conducted by the same experimenter (SS) and at the same time of day. Positioning adjustments on the horizontal leg press machine were recorded on laboratory form to aid in reproducing the subject setup for the retest session.

During the familiarization phase, the subjects were correctly positioned in the leg press machine (supine with the hip, knee and ankle joints flexed at ∼90°), and verbal instructions were provided on how to perform the coordinative test. The examiner then offered advice and answered any further questions but subjects were not allowed practice trials.

For the group A, warm-up (very short-term motor learning) consisted of four series of 10 concentric-eccentric repetitions at the leg press machine, performed unilaterally (for both lower limbs), with 1 min rest between each series. The range of motion at the knee joint was ∼90° and the load was comprised between ∼1/6 (16.6%) and ∼1/3 (33.3%) of the individual body mass. Then, the load was adjusted to ∼1/10 (10%) of the body mass, i.e., 5 kg, and subjects were allowed one-two 30 s practice trial of the coordinative test (see below), with both the dominant and non-dominant lower limb. The dominant lower limb was determined for each subject by asking which lower limb she would use to kick a ball with as far as possible [13].

The coordination test was completed unilaterally with a load minimizing force control (5 kg, ∼10% of body mass), and consisted of 60 s of target tracking during eccentric-concentric contractions of the lower limb muscles. Subjects were provided ongoing visual feedback of their position by means of a cursor (a sort of target) displayed on a video monitor in front of them. They were instructed to match a criterion trajectory (see Fig. 1) as accurately as possible, minimizing the difference between their performance and the criterion. With the exception of the first and last few seconds, the majority of the test was performed with a knee angle comprised between 70 and 10° of flexion. No feedback or advice was given by the examiner both during and at the end of the test. All the subjects performed the task with the dominant and the non-dominant lower limb and the test order was randomised. For each condition, two trials were completed and the average value of the two scores was retained for data analysis. Adequate rest periods (>1 min) were allowed between trials.

Tracking accuracy was quantified as proposed by the manufacturers of the Functional Squat System. The software calculated automatically the absolute average error (in cm), i.e., average of actual trajectory minus criterion trajectory for each data point, and the standard deviation (S.D.) of the average error. Both average and S.D. error were independently quantified as a function of the action mode (concentric versus eccentric) and of the tested lower limb (dominant versus non-dominant).

A four-way ANOVA with repeated measures on the last three factors was performed to study the effect of group (A versus B), dominance (dominant versus non-dominant lower

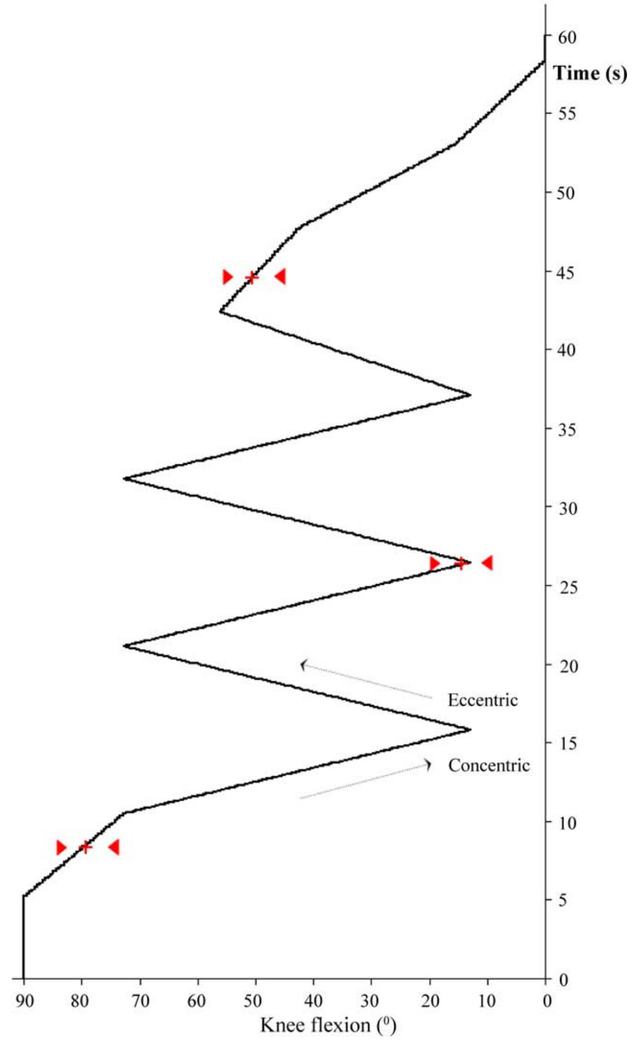

Fig. 1. A schematic representation of the tracking test used in this study. The concentric and eccentric phase, the criterion trajectory (thick line) and the actual position of the target at the beginning, in the middle and at the end of the test are also represented.

limb), action mode (eccentric versus concentric) and time (day 1 versus day 2, i.e., short-term motor learning) on dependent variables. When significant effect or interaction occurred, Tukey post hoc analyses were used to test differences among means. Test-retest reliability between day 1 and day 2 values was assessed by calculating a Pearson product correlation coefficient (r) and an intraclass correlation coefficient (ICC) using the ICC(2, k) model, as described by Shrout and Fleiss [18]. The ICC, which is a measure of correlation that considers variance, describes the agreement between the repeated measures. We used also the standard error of the measurement (SEM) to indicate absolute reliability and calculated it according to Atkinson and Nevill [1]. For all measures of reliability, dominant and non-dominant lower limb values were collapsed. The level of significance was set at $p < 0.05$ for the ensemble of the procedures. The statistical analyses were undertaken by using Statistica 6.0 (StatSoft Inc., Tulsa, Usa) and SPSS 11.0 (SPSS Inc., Chicago, Usa) for Microsoft Windows.

Table 1
Test-retest reliability (Pearson product correlation coefficient, r; intraclass correlation coefficient, ICC; standard error of the measurement, SEM) of average and S.D. error in the two experimental groups

	Average error	S.D. error
Group A ($n = 11$)	$r = 0.715$*	$r = 0.714$*
	ICC = 0.824**	ICC = 0.796**
	SEM = 0.023 cm	SEM = 0.053 cm
Group B ($n = 11$)	$r = 0.446$	$r = 0.808$**
	ICC = 0.590	ICC = 0.771*
	SEM = 0.028 cm	SEM = 0.064 cm

* $p < 0.05$.
** $p < 0.01$.

In group A, both average and S.D. error showed significant test-retest reliability (Pearson's r: $p < 0.05$; ICC: $p < 0.01$; Table 1), even if subjects from this group significantly enhanced their accuracy at the coordinative test performed on day 2. On the other hand, test-retest reliability was significant for S.D. error (Pearson's r: $p < 0.01$; ICC: $p < 0.05$), but low and insignificant for average error (Table 1) in those subjects who were not accustomed with the test (group B). Comparison of the SEM values with the calculated means indicated that the SEM values were relatively small for S.D. error but quite high for average error in both groups.

No significant main effects or interactions were found for average error (Table 2 and Fig. 2A), even if a tendency was observed for time (day 2 < day 1) and for time by action mode ($p = 0.084$).

Significant group (A < B) and time (day 2 < day 1) main effects were found for S.D. error (Table 2), while there was no significant influence of action mode and dominance. S.D. error showed a significant group by time interaction ($F = 4.37$, $p = 0.039$). Post hoc analyses evidenced that, at day 2, S.D. error significantly decreased in the group A (∼15%) but not in the group B ($p < 0.001$, Fig. 2B). Moreover, S.D. error of group A at day 2 was significantly lower than day 1 ($p < 0.001$) and also than group B values at day 2 ($p = 0.028$).

Table 2
F-values and p-levels for main effects associated to the 4-way ANOVA on average error and S.D. error

Variable	Main effect	F-value	p-level
Average error	Group	0.38	0.539
	Dominance	0.45	0.505
	Action mode	0.66	0.418
	Time	3.14	0.080
S.D. error	Group	5.28	0.024
	Dominance	0.09	0.760
	Action mode	0.05	0.823
	Time	11.93	0.0009

No significant interactions were found for average error. A significant group × time interaction was observed for S.D. error (see text and Fig. 2B for details).

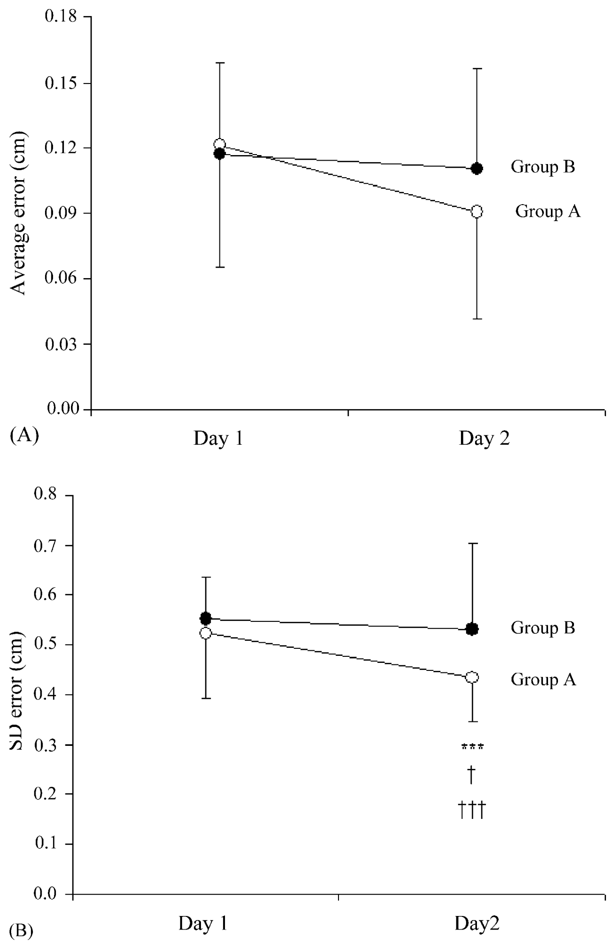

Fig. 2. Average error (A) and S.D. error (B) in the two experimental groups at days 1 and 2. Data (mean and S.D.) are collapsed for action mode and lower limb. (***) Significantly lower than day 1 ($p < 0.001$); (†) significantly lower than group B at day 1 ($p < 0.05$); (†††) significantly lower than group B at day 2 ($p < 0.05$).

The trajectory-tracking test proposed in the present study represents a good tool for the evaluation of motor coordination during multi-joint closed-kinetic chain action of the lower limb musculature. High test-retest reliability was observed for S.D. error but not for average error in the group of subjects considered unaccustomed. The obtained results suggest that action mode (eccentric versus concentric), side dominance and warm-up (very short-term motor learning) did not influence the outcome measure, therefore invalidating our preliminary hypotheses. However, S.D. error was significantly improved after one testing session, thus confirming the occurrence of short-term motor learning and the sensitivity of the present trajectory-tracking test. On the other hand, average error is probably not sensitive enough to detect significant improvement in tracking accuracy.

In the current study, intersession reliability was studied by correlating the average and S.D. error obtained at day 1 with respect to day 2 for both experimental groups. However, even though participants from group A were accustomed with the trajectory-tracking test – since their S.D. error significantly decreased from session to session (∼15%) – both average and S.D. error showed significant Pearson's r values and ICC values, therefore suggesting that the improvement was quite homogeneous for this subjects group. On the other hand, in group B – that was considered unaccustomed to the experimental test – reliability for S.D. error was quite high, while it was low and insignificant for average error. Together with SEM values, these findings indicate that S.D. error should be preferred to average error to characterise tracking accuracy in future studies. It is indeed possible that the poor reliability of average error is explained by the very low values (near to zero) associated to this parameter, as a result of the 'average' actual trajectory with respect to the 'average' criterion trajectory shown in Fig. 1. Therefore, an average error equal to zero should not necessarily be associated to an accurate test, since the concomitant S.D. error should be extremely high.

Tracking accuracy is typically quantified as the root-mean-square error between the criterion and the performance trajectory, this error being subsequently normalised to the total range of motion to give an accuracy index [8]. In our study, even though absolute S.D. error was quantified as the displacement of the leg press load (in cm), it is important to note that, due to the homogeneous composition of the present experimental groups, the same results were obtained when absolute S.D. error was normalised to the individual range of motion (group A: day 1: 2.62% and day 2: 2.16%; group B: day 1: 2.76% and day 2: 2.65%).

It was hypothesised that action mode would have influenced the outcome of our trajectory-tracking test, i.e., accuracy in the concentric phase of the movement would have been higher than under eccentric conditions. However, it was not the case. Our hypothesis was based on the fact that eccentric contractions are distinctly controlled by the central nervous system [11], with lower discharge rate and recruitment of fewer motor units with respect to concentric actions, which in turn result in greater fluctuations in acceleration [10], and therefore in lower movement accuracy. However, the fact that the absolute load adopted in this study was the same during eccentric and concentric actions (5 kg), while maximal voluntary strength at a given velocity is considerably higher in the former conditions, inevitably affected movement control during the extension phase of trajectory-tracking task. It is then possible that such an advantage during the eccentric phase of the movement was compensated by the neural disadvantage of lengthening contractions.

According to previous research on finger control [7,12], we also hypothesised that limb dominance would have affected the results of the present trajectory-tracking test, i.e., the non-dominant lower limb (the left for the majority of our subjects) would have tracked more accurately than the dominant. Hypothesis was also based on the fact that tracking skill requires processing of visuoperceptual and visuospatial relationships for which the right hemisphere is more specialized [4]. No difference was however observed between the two sides. It is indeed possible that the differences previously reported between preferred (or dominant) and nonpreferred side could not be extended to the lower extremities, mainly because of the respective solicitation during daily living activities, i.e., upper limbs are used more asymmetrically than lower limbs.

No difference was observed between the two experimental groups at day 1, i.e., there were no very short-term motor learning effects (warm up) on tracking accuracy. Significant improvements were however observed for S.D. error but not for average error at day 2 in those subjects who were well accustomed with the experimental protocol (group A). These findings confirm that a limited number of trials result in a significant improvement of tracking ability in healthy individuals through short-term motor learning [9]. These results also clearly demonstrate the sensitivity of S.D. error but not of average error to detect enhancement of tracking performance with repeated trials. Even though additional experiments are needed to evaluate sensitivity as well as intrasession reliability in larger groups (including healthy male subjects) and in individuals with movement disorders, the manufacturer should consider revising the variables provided by the software.

The unique aspect of our current study is the specificity of the trajectory-tracking test for rehabilitation and resistance training settings, but also for several activities of daily living. In 1988, Carey et al. [9] validated a force tracking test and a joint-movement tracking test for the hand and recommended to extend similar procedures to other joints. We were able to find only few studies on elbow flexors [3,14,15], and one on plantar flexors tracking ability [6], but none on multi-joint closed-kinetic chain functional movement such as simulated half squat. As a speculation, since lower limb muscles would behave very similarly during the eccentric-concentric actions considered here and during descending-ascending stairs, these findings would prove useful for investigating motor control and for identifying possible risk factors for falls in particular populations (e.g., elderly, obese). In turn, it should also be interesting to examine the effect of trajectory-tracking training as a means of preventing falls in these individuals.

A new tracking-trajectory test for the assessment of motor coordination has been proposed in the present study. The main outcome (S.D. error) has been shown to be reliable and sensitive to detect enhancement of tracking performance with repeated trials in healthy female individuals. Since the sample size used in this study is small, the generalizability of the results – for example to male subjects – is limited. It is nevertheless interesting to conjecture that, if gender differences in a lower limb task are similar to those reported for finger movements [7], i.e., men tracked significantly more accurately than women, test-retest reliability would be greater in male individuals. Potential applications of this test should be in the area of exercise physiology (e.g., to study the effect of fatigue, training or gender, see [7]), motor control (e.g., to investigate brain plasticity after tracking practice or training in both able-bodied and unhealthy individuals, see [12,16]) and sports medicine (e.g., in rehabilitation settings, where the horizontal leg press machine considered here is commonly used). The present test should be improved by concomitant quantification of the electromyographic activity of the muscles involved in the tracking task (see [5]) and by increasing the resistance on the leg press machine, in order to evaluate force control in addition to movement control [9].

Acknowledgements

Authors gratefully acknowledge all the volunteers that participated to the study.

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