Behavioural Brain Research 200 (2009) 7–14

Contents lists available at ScienceDirect

Behavioural Brain Research

journal homepage: www.elsevier.com/locate/bbr

Research report

Dynamic proprioceptive target matching behavior in the upper limb: Effects of speed, task difficulty and arm/hemisphere asymmetries

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ARTICLE INFO

Article history:
Received 8 June 2008
Received in revised form
18 November 2008
Accepted 21 November 2008
Available online 27 November 2008

Keywords:
Proprioception
Dynamic feedback
Kinesthesia
Laterality
Motor control
Feedback processing
Handedness
Sensorimotor integration
Memory
Interhemispheric transfer

ABSTRACT

Although proprioception consists of static (i.e. position) and dynamic (i.e. movement) components, most studies regarding the matching of proprioceptive targets have focused only on position. Further, these position-matching studies have recently indicated that proprioceptive ability is influenced by several factors including task difficulty and arm preference. The purpose of the present study, therefore, was to quantify the matching of dynamic proprioceptive target arm movements under different matching conditions. Using torque motor-driven manipulanda, 11 blindfolded, right-handed adults experienced triangular velocity profiles at 2 different peak speeds (30°/s or 60°/s) with the preferred and non-preferred elbow. Subjects then matched the dynamics of these target movements with either the same (ipsilateral remembered) or opposite (contralateral remembered) elbow. Matching errors were generally larger for the more difficult, contralateral remembered versus ipsilateral remembered task, and for greater target speed conditions. One arm difference was found indicating a non-preferred arm advantage for the matching of average target acceleration in the ipsilateral remembered condition. Overall, these results demonstrate that dynamic proprioceptive feedback-matching performance is influenced by several factors including peak speed, task difficulty and limb preference.

1. Introduction

The term proprioception was first coined by Sherrington [70] to describe a group of sensations elicited by stimulation of receptors within the body during one's own movement. While these sensations are thought to convey a variety of information, such as the force of a muscle contraction and the relative timing of motor commands [29,30], it is the ability to detect body segment positions and movements that has received the most attention to date. This bias is likely due to the vital role this type of information plays during the planning/execution of voluntary movements [16,17,39,50,51,58].

In general, it is well accepted that muscle spindle afferents are of primary importance in the conscious perception of limb position and velocity [50,73], although contributions are made by skin [27,53], joint [25,26] and Golgi tendon organ receptors [41]. The enhanced role of muscle spindles in signaling changes in limb position was, perhaps, best demonstrated by Goodwin et al. [37,38] in their classic studies using muscle tendon vibration. In these studies, high frequency, low amplitude vibration was applied to the biceps/triceps tendons of the preferred arm, as a means of increasing the firing rate of, primarily, group 1a muscle spindles [7,11]. During stimulation, participants were then asked to use the opposite arm to indicate either the position, or speed and direction, of the vibrated arm. As a consequence of these vibration-induced increases in muscle spindle firing rate, illusory effects in the perception of both elbow joint position and velocity were shown, which were consistent with perceived lengthening of the vibrated muscle. These results were expanded upon by Sittig et al. [71,72] who found differential effects of biceps/triceps tendon vibration on elbow position and velocity sense during the matching of a visual target, as well as in response to different frequencies of vibratory stimulation ranging from 0 to 125 pps.

Compared to velocity sense, the ability to perceive and replicate joint positions based on proprioceptive information has been far more extensively studied, with errors of less than 5° typically reported [2,3,18,47,49,78]. Recent studies by this laboratory [33–36], however, have revealed that the accuracy of proprioceptively based position sense is significantly influenced by both the type of matching task employed, and the arm used to perform the matching movement. Specifically, subjects made larger matching errors in a condition requiring memorization and hemispheric transfer of proprioceptive information, which are thought to reflect increased processing demands. Further, matches made by the pre-

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doi:10.1016/j.bbr.2008.11.034

ferred versus non-preferred arm were less accurate in terms of absolute error. This latter finding is particularly intriguing, as it suggests a right hemisphere advantage for the utilization of proprioceptive feedback [32].

In contrast to studies of position matching, the ability to match the dynamics of upper limb movements based on proprioceptive feedback has been largely ignored in the motor behavioral literature. This is surprising given the key role dynamic proprioceptive feedback is known to play in the control of many coordinated upper limb movements. A clear demonstration of this can be found in studies involving individuals with proprioceptive deficits due to large fiber neuropathy. Sainburg et al. [65], for example, had deafferented participants perform a movement sequence task that mimicked slicing a loaf of bread. In this case, dynamic movement performance was characterized by increased wrist-path trajectory curvatures, and significant temporal decoupling between shoulder and elbow joints. Similar deficits have also been reported for tasks involving the tracing of lines oriented in different directions [63] and visual target matching in three-dimensional space [52], where control of the dynamic aspects of movement is required.

Of the few studies quantifying the perception of arm speed/dynamics in the absence of vision, most have utilized velocity-discrimination paradigms where a speed comparison has been made between two successive movements [20,42,48]. In these studies, conducted using only the preferred arm, the primary finding to emerge was a speed effect where subjects were more accurate in discriminating slower criterion target speeds. Beyond these studies, Cordo et al. [17] explored the effects of biceps tendon vibration on the ability to match elbow velocity with the contralateral limb. This study showed significant effects of vibration on matching ability. However, no measure of matching accuracy specific to non-vibrated conditions was provided.

One known report has quantified the ability to perceive and replicate dynamic characteristics of upper limb movement [48]. Lonn et al. required right-handed subjects to match the speed of both self-generated and passively experienced target shoulder movements. Similar to velocity discrimination studies [20,42,48], it was again shown that subjects were more accurate when matching self-generated target movements that had slower peak velocities. In this case, however, subject performance was only assessed with respect to errors in peak and average speed measures, and not for other aspects of the target movement such as acceleration, deceleration, movement amplitude, velocity profile symmetry or duration. Well-learned goal-directed movements are typically characterized by unimodal, bell-shaped velocity profiles where equal periods of time are spent accelerating and decelerating the limb [8–10,28,54] Thus, assessment of additional parameters may reveal important information, given that greater feedback utilization is thought to differ during the early versus late period of movement [23,24,74,77]. In contrast, more feedforward strategies may be employed during the acceleratory portion of movement in order to compensate for inherent feedback delays within the nervous system [19].

The purpose of the present study was to further elucidate the accuracy by which healthy individuals can perceive and replicate the dynamics of a proprioceptively determined target arm movement. Healthy young subjects were asked to complete a series of proprioceptively based target matching tasks that varied in terms of speed, task difficulty and arm used to perform the matching movement. Multiple movement characteristics were assessed with the hypothesis that accuracy would be significantly worse for greater peak speed targets and during the more difficult matching task, which required both memory and interhemispheric transfer of target information. In addition, smaller matching errors were also anticipated for matches made by the non-preferred versus preferred arm, based on previous results from this laboratory for position matching [33–36]. Lastly, a task by matching arm interaction was expected whereby any non-preferred arm advantages would be most prevalent in the more difficult contralateral remembered task.

2. Materials and methods

2.1. Subjects

Eleven healthy, young adults (mean age 20.5 ± 2.7 years) participated in the study. All procedures were approved by the research ethics review board of the University of Michigan and, therefore, complied with the ethical standards laid down in the 1864 declaration of Helsinki. Subjects were free of upper limb neuromuscular impairment at the time of testing and showed a strong right arm preference for common tasks of daily living. This was quantified using a ten-item version of the Edinburgh Handedness Inventory [57] with all subjects having a laterality quotient score of greater than +90.

2.2. Experimental setup

The setup for this experiment, depicted in Fig. 1, consisted of two servo-motor driven manipulanda devices designed for elbow displacement in the horizontal plane. Blindfolded subjects were seated with forearms resting comfortably on length and height-adjustable aluminum levers. Rotation of the levers about the elbow joint occurred by either active movement of the subject, or via the programmable servomotor system. Standardized start positions were maintained for the shoulder (80° abduction, 15° flexion), elbow (75° extension) and wrist (neutral) joints across subjects. The effects of altered head position were minimized by means of a chin rest and support frame surrounding the lateral aspects of the head.

2.3. Experimental procedures

Subjects were asked to complete a series of proprioceptively based dynamics matching tasks consisting of two phases. In the first phase, target determination, the subject's elbow was passively extended by the servomotor system following one of two target triangular velocity profiles. In the 30°/s peak speed condition, the forearm was accelerated for 1 s at 30°/s/s to a peak speed of 30°/s, and then decelerated at -30°/s/s for 1 s back to rest. Similarly, in the faster, 60°/s peak speed condition, the forearm was accelerated for 1 s at 60°/s/s to a peak speed of 60°/s, and then decelerated at -60°/s/s for 1 s bask to rest. In both conditions, the elbow was returned after 1 s to the start position following the same speed trajectory, but in the opposite movement direction.

Immediately following the elbow's return to the starting position, the target-matching phase of the procedure began. Subjects were given an auditory signal that coincided with disengagement of the motors. Upon this cue, subjects were to match the "way their arm had been previously moved without focusing on its final position". This was accomplished through active extension of either the same (ipsilateral remembered condition) or opposite (contralateral remembered condition) elbow. Matches made in the ipsilateral remembered condition were thought to consist largely of the memory-based storage and retrieval of dynamic proprioceptive information. In contrast, contralateral remembered matching required both memory and interhemispheric transfer of dynamic proprioceptive feedback. Once matching was completed, the subject's arm was subsequently returned to the start position at a constant speed of 15°/s in preparation for the next trial.

2.4. Data collection and analysis

For each peak speed (30°/s vs. 60°/s), task (ipsilateral remembered vs. contralateral remembered) and arm (preferred vs. non-preferred) condition five trials were completed in a random block design. Specifically, each combination of arm and task was blocked and presented in a random order, while peak target speeds were fully

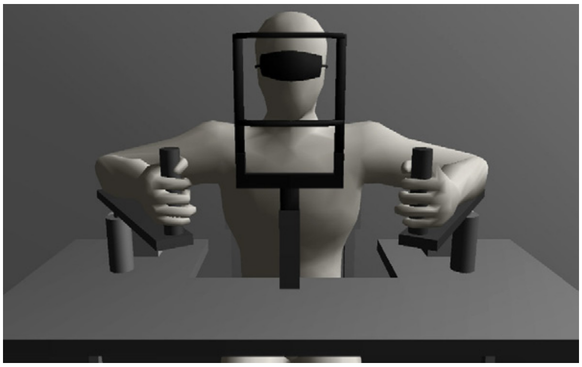

Fig. 1. Experimental setup for speed/dynamics matching task employed in this study.