Velocity modulated decision making in a reaching task

by

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Abstract

Humans can compensate rapidly to unforeseen errors and circumstances while performing motor tasks. These tasks are exposed to sensory and motor noise and delays originated from the biological system characteristics, as well as to varying surrounding environments while performing movements. Therefore, uncertainty of the estimate of limb position arises. Error estimates during movement and displacements after a mechanical perturbation are compensated by relying on proprioceptive feedback from the body. Moreover, the motor system can rely on co-contraction as it increases the amplitude of the short latency stretch reflex, which plays an important role in minimizing the effects of disturbances. This study examines the influence of position, velocity, and pre-perturbation background muscle activity in the decisional process of avoiding obstacles in the environment after a mechanical perturbation while performing a reaching task. After the perturbation, participants had to choose between two strategies: going in between or around the obstacles to reach an end target. Position of the hand, velocity, and EMG activity of four muscles in the shoulder and elbow were compared at different time epochs between both strategies. No significant differences were found in muscle activity pre-perturbation and lateral position before and up to 100ms after perturbation onset. Significant difference in lateral velocity was found 50ms after perturbation onset between the two strategies. Online corrections to avoid obstacles after a mechanical perturbation are modulated by the lateral velocity of the limb.

Keywords: *upper-limb, co-contraction, decision making, obstacle avoidance, motor control*

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Introduction

Humans have the ability to learn and execute an immense amount of motor commands to perform specific movements of the limbs, as well as to compensate for unforeseen errors and circumstances while performing motor tasks. The flexibility to adapt rapidly to changes suggests that the brain uses information from the body and a planning of a specific motor action to have control over the movement of the limbs (Rossetti, Prablanc, Desmurget, & Pe, 1998; Sarlegna & Sainburg, 2009). Over the years, there have been different theories regarding how the central nervous system (CNS) controls movements, with the feedforward and the feedback frameworks being the most widely studied.

The central nervous system relies on feedback information from proprioception to be able to coordinate the movement from the limbs. Proprioception is the unconscious perception of movement, forces, and location of body parts in space and in relation to our body. Proprioception arises from sensors that respond to specific stimuli called proprioceptors, which occur in skeletal muscles, tendons, joints, ligaments, and connective tissue. Additionally, in order to execute different motor tasks, the CNS relies on visual information to define the kinematic plan of the movement (Sarlegna & Sainburg, 2009). The use of proprioception can be affected by various factors in the absence of visual information. When making movements to a target, endpoint errors of the limbs increase as movement amplitude (Goble & Brown, 2009) and their location with respect to the body increase (Van Beers, Sittig, & Denier Van Der Gon, 1998).

The nervous system responds to unanticipated mechanical perturbations with a series of bursts of muscular activity. The short latency stretch reflex is the earliest response to a mechanical perturbation. It reflects spinal processing of the stretch, reason for which it happens so fast and is mediated largely in the upper limb by the spinal monosynaptic and oligosynaptic reflex pathways (Burke, Gandevia, & McKeon, 1984; Hammond, 1955; Manning & Bawa, 2011). Following the short latency stretch response, there is another burst in muscular activity denoted the long latency stretch response. This second burst has more flexibility and can adapt to changing environmental conditions, limb dynamics and task requirements (Pruszynski & Scott, 2012). Studies in postural tasks have led to believe that short and long-latency reflexes contribute to modulation of limb stiffness (Dietz, Discher, & Trippel, 1994; Doemges & Rack, 1992).

The modulation of mechanical properties of the arm can have an impact on how it responds to perturbations. In a position regulating task, a higher joint impedance provides mechanical advantage in response to unknown forces. Via co-contraction – the simultaneous activation of pairs of agonist and antagonist muscles around a joint– the nervous system can increase joint stability and minimize position offset caused by a perturbation. Co-contraction can be used as a strategy to minimize perturbations (Milner & Cloutier, 1998) and to facilitate movement accuracy. (Gribble et al., 2003; Morishige, Osu, & Kamimura, 2007).

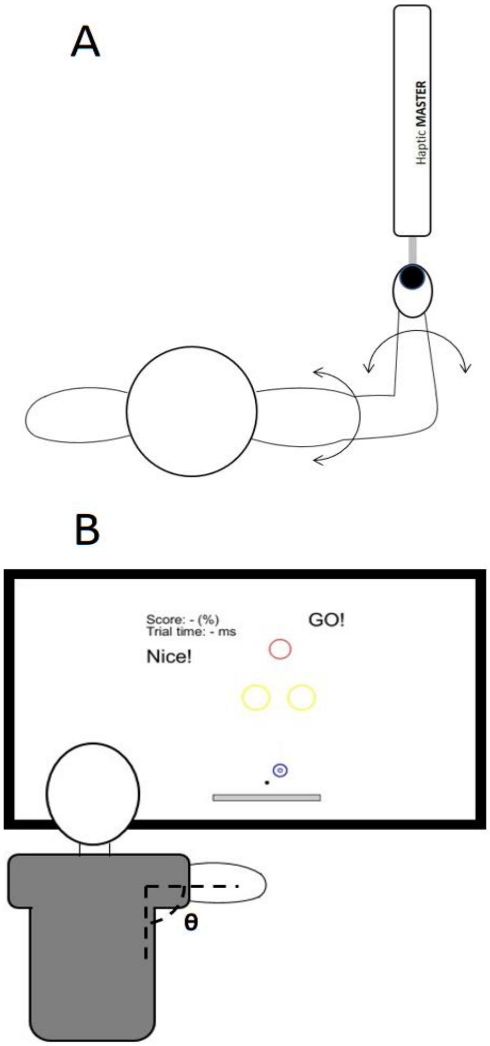


Figure 1. Experimental Setup. A, Top view of the participant holding the robotic device (Haptic Master). Robotic device allowed movement in the horizontal plane. Limb configuration at starting position: Elbow ≈ 90° flexion, abduction of the arm ≈ 90°. B, Back view, visual hand feedback was presented via a TV monitor in front of the participant.

Motor control mechanisms implemented by the CNS must consider mechanical perturbations in the environment, movement variability, and task goal. The theoretical framework of Optimal Feedback Control (OFC) has been gaining influence in the field, as it considers these factors. OFC resolves how a behavioral goal has to be achieved by minimizing the cost of effort of performing the movement (Todorov, 2004). In a recent study, a series of experiments were performed to analyze how sensory feedback influenced online movement control during a reaching task in a complex environment without visual feedback (Nashed & Scott, 2014). The OFC model they propose, uses the hand position estimate to determine the movement strategy used to avoid obstacles after a mechanical perturbation while performing a reaching task. The study concludes that strategy selection is position dependent at perturbation onset. One of their participants was excluded from the experiment due to excessive co-contraction, a strategy that could be used to learn a novel task and eventually be reduced through practice and learning of the task (Osu et al., 2002).

Their analysis focuses on the lateral positions 50ms after perturbation onset, but suggests that velocity could also influence the decisional process. Furthermore, increased muscle activity of the excluded participant before the experiment could indicate his intention of using co-contraction to learn the task. This increase in activity could become a determinant factor in the decisional process as co-contraction of the muscles increases the amplitude of the short latency stretch reflex, which plays an important role in minimizing the effects of disturbances (Scott, Cluff, Lowrey, & Takei, 2015).

Through the use of feedforward models, the CNS predicts position and velocity of the limb during movement execution. Certainty of these predictions is not guaranteed, as the sensory and motor signals are affected by noise and delayed by the biological characteristics of the system (Faisal, Selen, & Wolpert, 2009). Additionally, the inconsistency of end-point accuracy of proprioceptive guided movements (Jones, Cressman, & Henriques, 2010; Van Beers et al., 1998) casts serious doubts of their reliability as a determinant factor for the OFC model.

There is a need for a greater understanding on how muscular activity and proprioceptive feedback affect the different control strategies that the CNS employs to regulate movement. The purpose of the present study is to analyze how position, velocity, and pre-perturbation muscle activity influence the decisional process of avoiding obstacles while performing a reaching task.

Subjects were asked to perform a series of movements to a target while avoiding obstacles to the right and left of the reaching path. Muscular activity in the upper limb was assessed with the hypothesis that a higher activation of the flexor-extensor muscles of the elbow and shoulder before a perturbation will modulate the decision to navigate between or around the obstacles.

Materials and Methods

Participants

A total of 9 subjects (6 males and 3 females, all which reported right-hand dominance) participated in the experiments. The TU Delft Ethics Committee Board approved the experimental protocol. Experiments lasted ≈2h.

Apparatus

For the experiments, a robot device (Haptic Master, Moog FCS Robotics) was used, allowing movements in the horizontal plane. The Haptic Master simulated mass was set to 2kg, with a friction coefficient of 0.001. The robot device was coupled to a Bachmann controller, which permitted manipulation of forces and the recording of position, velocity, and force data at 1000 Hz. The control system was developed using the Simulink environment of MATLAB (Version 15b, Math-Works Inc.), which connected to the Bachmann controller and the Haptic Master. Projected start position, targets, obstacles, and hand feedback (Figure 2) were presented to the subject via a TV monitor (UE40H6400AW, Samsung) with a refresh frequency of 25 Hz.

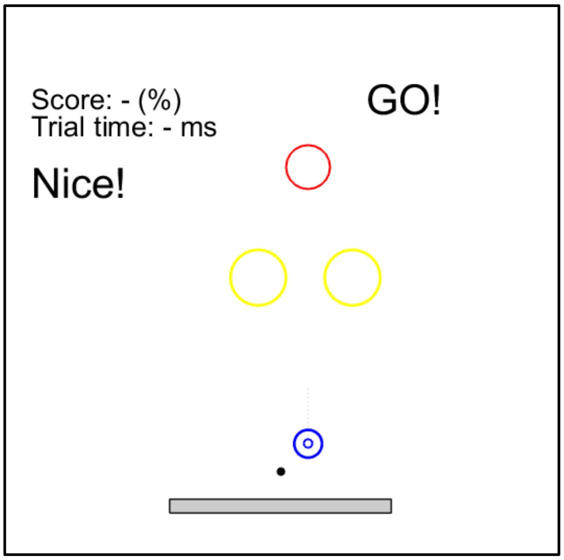


Figure 2. Visual feedback presented to the participant in TV monitor. The black dot represents the position of the hand in the horizontal plane. The blue circle represents the start position, the red circle represents the end target and the yellow circles represent the obstacles. Upper right corner displays instruction to "Hold!" (position) or "Go!". After completion of each trial feedback is given in the upper-left corner, displaying accumulative score, trial time and text indicating performance.

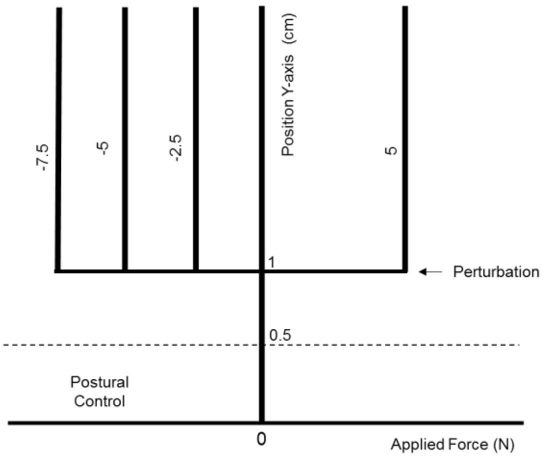


Figure 3. Force perturbations applied to the hand of the participant in the X-axis direction. Before movement onset, postural control was required from the participant by remaining inside the start target (radii 0.5 cm) for 1000 milliseconds before movement onset. After movement and at a distance of 1 cm from the start target, step-forces were applied to the hand, which displaced the hand's position.

Surface electromyographic (EMG) recordings where obtained from the following four flexor and extensor muscles of the elbow and shoulder of the right arm: Biceps Brachii (BB; elbow flexor), Triceps Lateral (TL; elbow extensor), Pectoralis Major (PM; shoulder flexor), and Deltoid Posterior (DP; shoulder extension). Skin surfaces were lightly abrased with a skin preparation gel and cleaned with alcohol. A two-bar electrode (DE-2.1 Delsys, Boston, MA) was then fixed to the skin over the muscle belly (full procedure of electrode placement and clinical test for each muscle is provided in Appendix A). The reference electrode (UltraStim, 5 cm round electrode) was placed on the right wrist.

Experimental Protocol

Experiment 1: Resting EMG

The experimental protocol started by measuring the resting activity of the muscles of the participant. The participant was asked to sit down erect, with arms hanging by the sides and the hand facing upwards resting on the anterior thigh. The participant was instructed to relax and remain still while a 10 second measurement of muscular activity was recorded.

Experiment 2: Obstacle placement

Table 1. Mean and SD of obstacle position for all participants

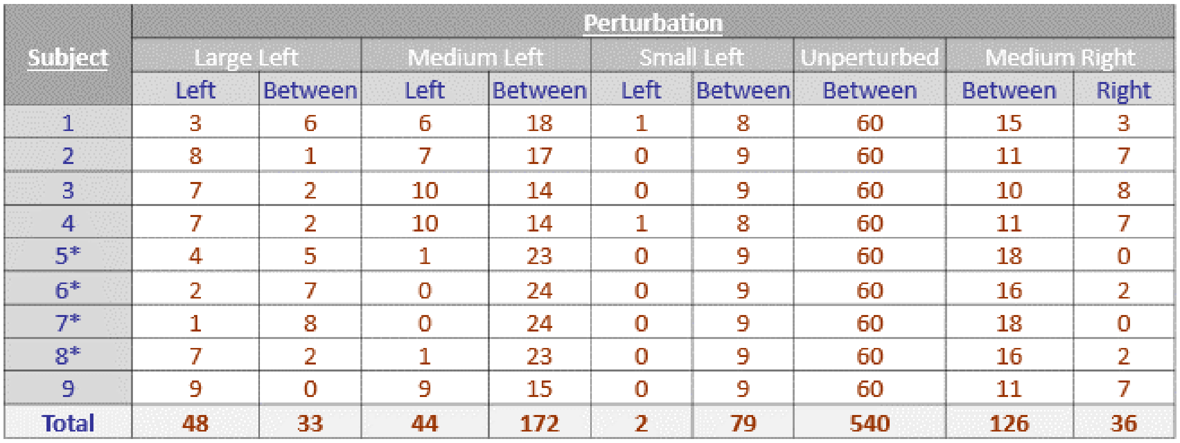
	Obstacle Position (cm)	
	Left	Right
Mean	-2.167	1.798
SD	0.457	0.670

The experiments began with a preliminary test of the subject's corrective response to perturbations. The participant was sitting down, with limb configuration at the start target: elbow ≈ 90° flexion, abduction of the arm ≈ 90°, shoulder ≈ 0° with respect to the coronal plane, grasping the end effector of the robot device with the forearm in a neutral position (Figure 1). All subjects were required to stabilize and hold their hand position within the start target (radius 0.5 cm) for a time of one second before movement. After the hold period, a visual instruction to start movement was given to the subjects. Participants were instructed to perform simple reaching movements after the visual stimuli, while told that this was not a reaction time test. The participants performed reaching movements from the start target to an end target (radius 1 cm) located 10 cm in front of the start target. After movement onset, visual feedback of the hand position was removed. As participants approached the end target (within 2 cm) visual hand feedback was restored so that they could attain the spatial goal, where they had to hold position for one second to complete the trial. Trial time started as soon as the participants exited the start target and ended when they reached the end target. After trial completion, participants were given visual feedback as to whether they obtained the required speed criteria (Success: "Nice" and one point awarded in score. Failure: (1) time < 800ms, "Too fast" and no point awarded in score; (2) time > 1200 ms, "Too slow" and no points awarded in score). Score measure was displayed to engage the participant on the task.

On half of the trials and with random order, step forces were applied to the hand after movement onset, exactly 1 cm in front of the start target. Forces of 5 N and -5 N were applied, deviating the hand to the left or right, respectively. After a familiarization block, the participant performed one block, which interleaved 20 unperturbed trials and 20 perturbed trials (10 left and 10 right) for a total of 40 trials.

The left obstacle placement (Table 1) for Experiment 3 was calculated using the mean lateral deviation on the X-axis 6 cm in front of the start target over the left perturbed trials. The right obstacle placement was determined in the same

Table 2. Obstacle avoidance decision by subject and perturbation



Subject	Perturbation								
	Large Left		Medium Left		Small Left		Unperturbed	Medium Right	
	Left	Between	Left	Between	Left	Between	Between	Between	Right
1	3	6	6	18	1	8	60	15	3
2	8	1	7	17	0	9	60	11	7
3	7	2	10	14	0	9	60	10	8
4	7	2	10	14	1	8	60	11	7
5*	4	5	1	23	0	9	60	18	0
6*	2	7	0	24	0	9	60	16	2
7*	1	8	0	24	0	9	60	18	0
8*	7	2	1	23	0	9	60	16	2
9	9	0	9	15	0	9	60	11	7
Total	48	33	44	172	2	79	540	126	36

* Participants excluded from the results of Experiment 3.

manner as the left obstacle, nevertheless using the right perturbed trials.

Experiment 3: Obstacle avoidance and target selection after perturbation

After the second experiment, the participant was asked to perform similar reaching movements with two virtual obstacles in the environment. The virtual obstacles (radii 1 cm) provided mechanical feedback when contacted and were located to the right and left of the unperturbed hand trajectory. Obstacles were located 6 cm in front of the start target and were strategically placed to block the path created by the corrective responses in the second experiment.

On selected trials, one of four different perturbation forces (Figure 3) was applied to the hand: (1) Medium Right: 5 N; (2) Small Left: -2.5 N, (3) Medium Left: -5 N, and (4) Large Left: -7.5 N. The participant had to counter the forces and reach into a single target. The activation position of the step force, target size and location was similar to those in Experiment 2. The subject performed 3 blocks, consisting of interleaved 20 unperturbed trials, 14 leftward perturbation trials (3 small, 8 mediums, and 3 large), and 6 rightward perturbation trials, for a total of 60 unperturbed trials and 60 perturbed trials.

Data Management

The data was processed in MATLAB and then exported to SPSS (Version 24, IBM Corp.) for statistical analysis.

Data Analysis

Exclusion criteria participants. Main interest in the study is to analyze how muscle activity pre-perturbation affects the decision of navigating between or around obstacles in the path for the middle left perturbations. Participants 5 to 8 had >95% of the trials going in between the obstacles (Table 2), for which they were excluded from the result analysis of Experiment 3.

Exclusion criteria trials. Trials in which the participant could not avoid the obstacle and bumped into it, were excluded from the analysis, as well as trials in which speed criteria was not met.

Muscle Activity Processing and Normalization. All recorded data were aligned on perturbation onset. Pre-processing of the EMG signals included an

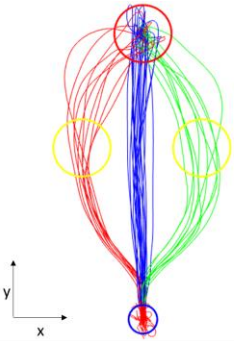


Figure 4. Movement trajectories in Experiment 1, obstacle placement. Hand trajectories from a representative subject for each of the perturbation conditions. Red and green trajectories represent perturbed trials to the left and right, respectively. Unperturbed trials are shown in blue. Position in the x-axis for the obstacles (yellow circles) is calculated finding the mean of displacement 6cm from the start target

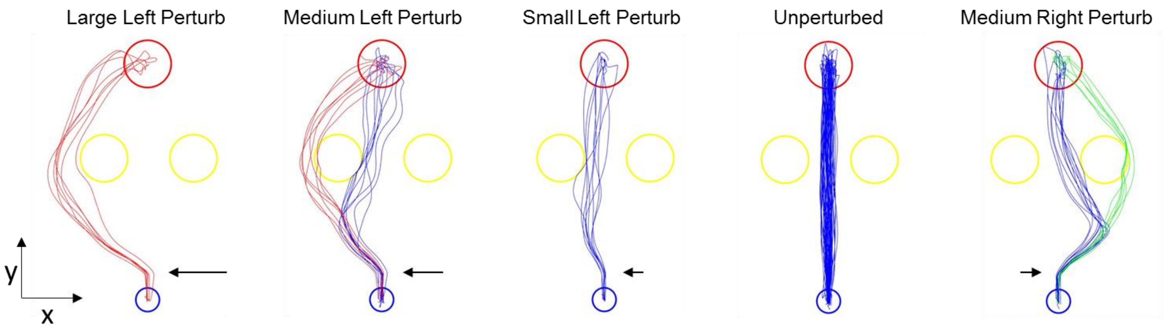


Figure 5. Movement trajectories for an exemplar subject for all perturbations. Red, blue, and green trajectories indicate those that went to the left of both obstacles, between both obstacles, and to the right of both obstacles, respectively. Black arrows indicate the position and magnitude of perturbance. For medium left and medium right perturbations, two distinct strategies are observed: to go between or around obstacles.

amplification (gain = 1 K), bandpass filtering (20–450 Hz) and digital sampling at 1000 Hz. EMG measurements for each muscle were full wave rectified and processed with a causal moving average filter with a window size of 40 ms to create an envelope signal. This window size was chosen subjectively, as it produced an envelope that profiled bursts of activity. EMG signals were normalized for each muscle by their mean in Experiment 1.

Epochs of muscle activity were categorized temporally according to previous studies (Crago, Houk, & Hasan, 1976; Dietz et al., 1994; Nakazawa, Yano, & Yamamoto, 1997):

- pre-movement (-500 to -400 ms)
- movement onset (-400 to -200 ms)
- long pre-perturbation (-200 to 0 ms)
- pre-perturbation (-50 to 0 ms)
- R1 (25 to 45 ms)
- R2 (45ms to 75ms)
- R3 (75-105 ms)
- Vol (105-145 ms)
- Vol2 (145-200 ms)

To estimate the amount of co-contraction in the limb, a similar method to the “wasted contraction” (Gribble et al., 2003; Thoroughman & Shadmehr, 1999) was used: a mean muscle activity (MMA) measure across the limb was calculated for each of the epochs by averaging the four muscle recordings. The resulting value represents the magnitude of normalized EMG activity across the opposing muscles of the limb, which increase stiffness. Although this method is subject to many simplifications (see Discussion), it gives an estimate of muscle co-activation across the limb during the movement.

Kinematics. The CNS relies on feedback information from the muscles to evaluate a response to mechanical perturbations. Nashed, et al’s study showed that strategy selection was lateral position dependent and suggests that decision likely considers lateral velocity as well. To determine if position and velocity have any influence in the decisional process to navigate between or around the obstacles, they were compared at different times for those trials in which the medium left perturbation was applied. Position and velocity were evaluated at the following temporal instances:

- 0ms (perturbation onset)
- 50ms
- 100ms
- 150ms

Probability distributions were estimated using a Kernel Smoothing function estimate for illustration purposes only.

Table 3. Subject data for trials that avoided the obstacles for the middle-left perturbation.

Subject	Choice		N	% of total trials
	Left	Between		
1	6	16	22	92%
2	4	5	9	38%
3	10	11	21	88%
4	9	13	22	92%
9	8	9	17	71%
Total	37	54	91	76%

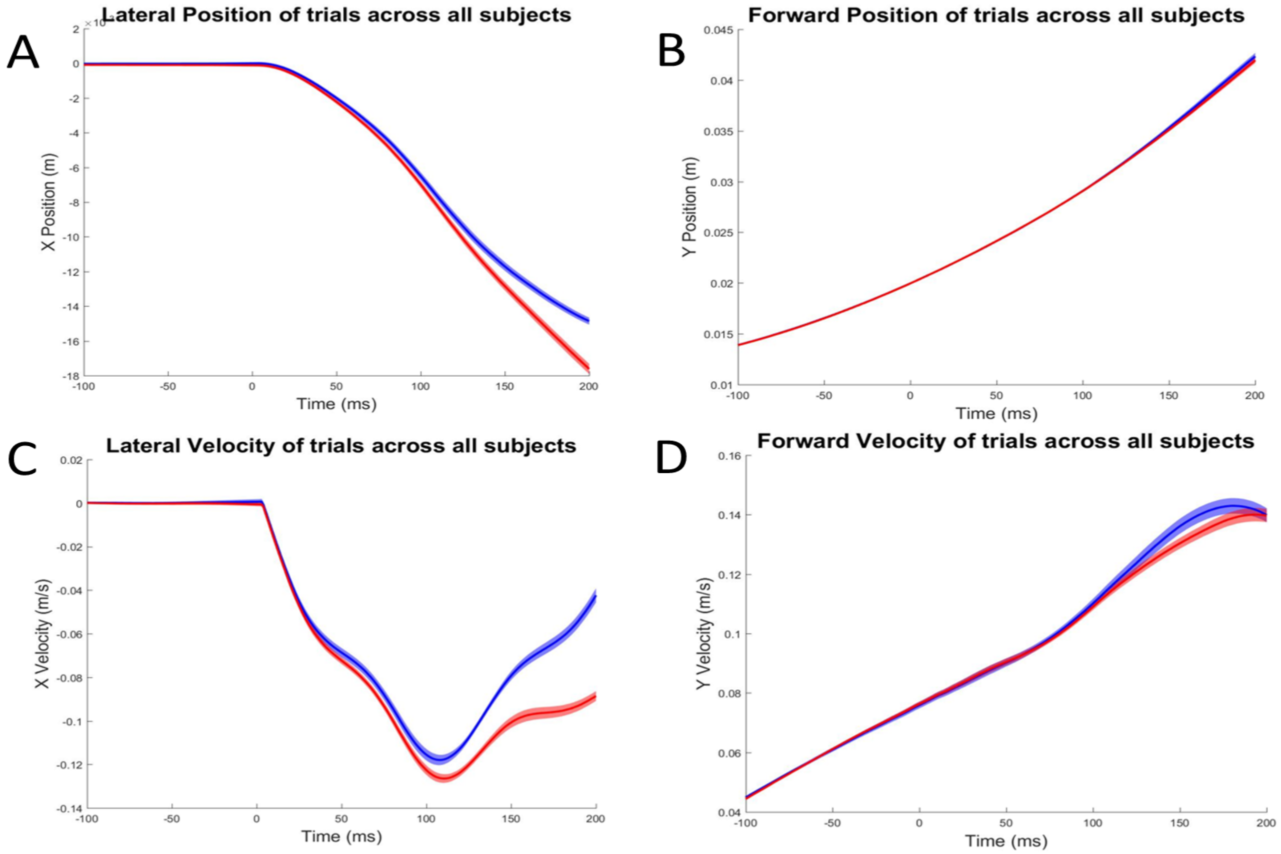


Figure 6. Kinematics of trials that went in between and around obstacles across all subjects. A, mean and SE of the X-position across the movement. Red and blue trajectories represent trials that went outside of both obstacles and between both obstacles, respectively. B, mean and SE of Y-position across the movement. C, mean and SE of the X-velocity across the movement. D, mean and SE of Y-velocity across all movement.

Statistics. To evaluate the effect of position and velocity of each strategy for the middle left perturbations, a MANOVA test were performed using IBM SPSS Statistics software. Similarly, a MANOVA test was performed to evaluate significance of EMG epochs for the four muscles and the MMA measure versus the choice. Finally, to evaluate if muscle activity pre-perturbation had any influence in position at perturbation onset, correlation tests between EMG of TL and MMA against position were performed.

Results

Experiment 1: Obstacle Placement

After the familiarization block, participants performed the series of 40 trials, with 20 unperturbed and 20 perturbed trials. For the unperturbed trials, participants performed straight reaching movements with bell-shaped velocity profiles. During the perturbed trials, hand trajectory was deviated to the right or left of the unperturbed path. Participants countered the forces and made corrections to achieve the spatial goal. The hand movement trajectories can be clearly distinguished between each of the perturbation conditions (Figure 4). The average position for the obstacle placement being ≈ 2 cm from the straight path between obstacles with a SD of ≈ 0.5 cm.

Experiment 2: Obstacle avoidance after perturbation

Figure 5 displays the behavior of an exemplar subject for all perturbations. For this experiment, the interest was in comparing the muscle activity between the two strategies that the participants followed for the medium sized perturbations. In unperturbed trials, reaches to the end target were straight with a bell-shaped velocity profile. For small perturbations, the force was quickly countered and the movement was corrected to pass between the obstacles and reach the end target. In large left perturbations, subjects altered

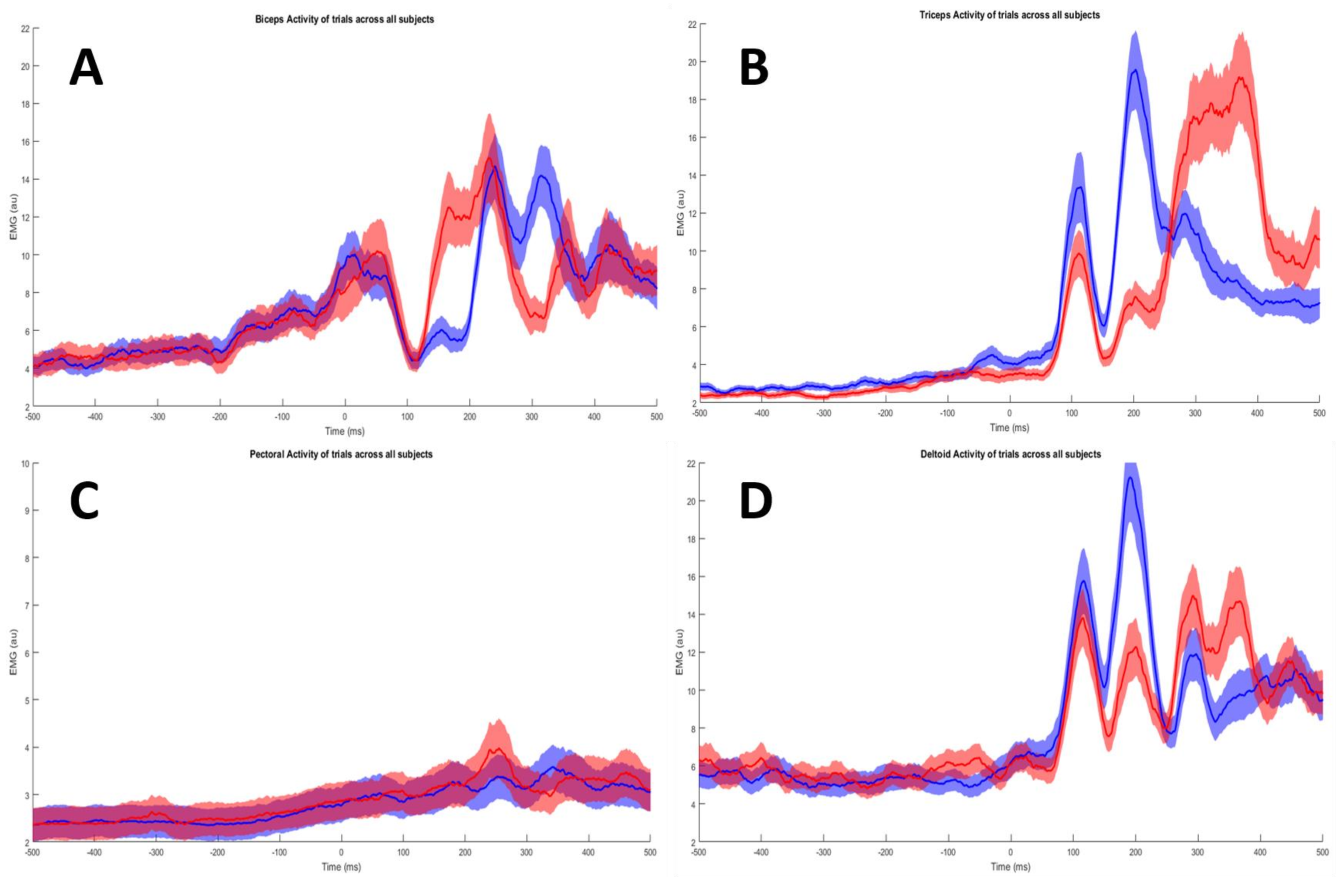


Figure 7. Muscular activity of the BB, TL, PM, and DP muscle. Red and blue trajectories represent trials that went outside of both obstacles and between the obstacles, respectively. Solid line indicates mean and shaded area indicates the SE.

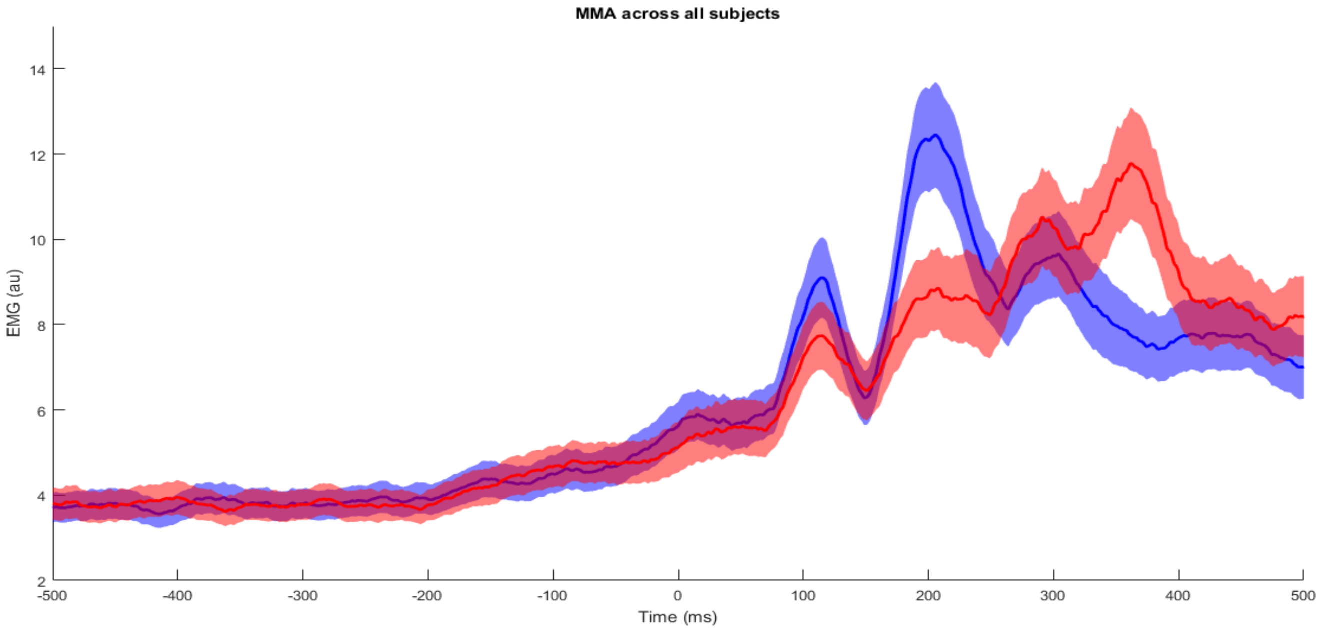


Figure 8. MMA across all subjects by choice. Red and blue trajectories represent trials that went outside of both obstacles and between both obstacles, respectively. Solid line indicates mean and shaded area indicates the SE.

the trajectory of the hand by changing to an alternate path and going around the obstacles to reach the end target. Middle left perturbations yielded two distinct strategies: trajectories that navigated between and around the obstacles. Table 3 shows the amount of trials in which the participants avoided the obstacles and the choice of going in between and around the obstacles for the medium-left perturbation. On average, approximately 60% of the trials went between the obstacles versus around the obstacles. Subject 2 had the lowest obstacle avoidance with ≈40%, while the rest of the participants avoided the obstacles in >70% of the trials.

The main interest was analyzing muscular activity in medium left perturbations. EMG was recorded of the four muscles involved in flexion-extension of the elbow and shoulder. Their mean activity throughout different temporary epochs were calculated to compare between the two distinct strategies. In the pre-movement epoch (-500 to -400 ms), muscle activity was similar for all muscles: BB (P(1,0.190) = 0.664),TL (P(1,0.674) = 0.414), PM (P(1,0.171) = 0.680), DP (P(1,1.598) = 0.210) and MMA (P(1,0.144) = 0.709).

The movement onset (-400 to -200 ms) epoch, reflected the same results as the pre-movement epoch, with no dissimilarity between activity across all muscles and MMA: BB (P(1,0.030) = 0.862, TL (P(1,0.791) = 0.377), PM (P(1,0.936) = 0.336), DP (P(1,0.185) = 0.669) and MMA (P(1,0.570) = 0.821).

Pre-perturbation epochs (-200 to 0 ms and -50 to 0 ms) were analyzed to assess the influence of muscle activity in the strategy selected, with no significant difference found in all muscles and MMA. Long pre-perturbation: BB, P(1,0.189) = 0.664; TL, P(1,0.931) = 0.338; PM, P(1,2.538) = 0.115; DP, P(1,1.982) = 0.163: and MMA, P(1,0.008) = 0.929. For the pre-perturbation epoch: BB, P(1,0.249) = 0.619; TL, P(1,2.302) = 0.133; PM, P(1,0.559) = 0.457; DP, P(1,0.142) = 0.708: and MMA, P(1,0.601) = 0.441.

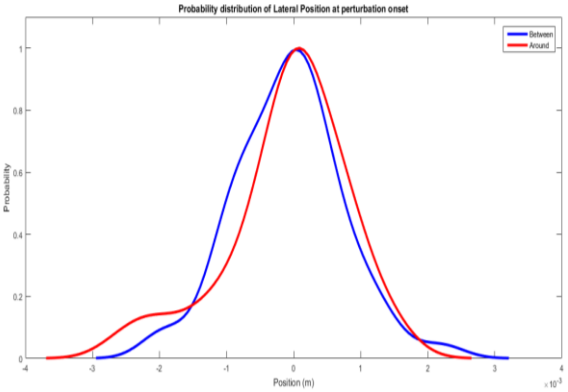


Figure 9. Probability distribution estimate of Lateral Position at perturbation onset. Blue and red line represent distributions for trials that went between and around the obstacles, respectively. No significant difference is found between positions at perturbation onset.

While not the main goal in this study, post-perturbation activity of the main stretched muscle, TL, was examined to identify the time in which the motor system reflected each of the strategies.TL activity during (Figure 7 B) the R1 response (25 to 45 ms) was similar between both strategies (P(1,1.784) = 0.185). No significant differences in EMG was found for the R2 (45ms to 75ms), R3 (75-105 ms) long latency time periods (R2: P(1,1.155) = 0.286 and R3: P(1,1.584) = 0.212), and for the voluntary epoch Vol (105-145ms) (P(1,3.211) = 0.077). Significant differenc was found at the voluntary epoch Vol2 (145-200ms) (P(1,31.354) < 0.0005). Analysis of MMA over the same time epochs to assess influence of co-contraction level after perturbation yielded the same results as TL, with no significant differences for R1 (P(1,0.324) = 0.571), R2 (P(1,0.240) = 0.626), R3 (P(1,1.205) = 0.276), and Vol (P(1,2.220) = 0.140) epochs; while significant difference for the Vol2 (P(1,37.605) = 0.010) epoch was found.

No dependency of choice to lateral position was found at perturbation onset (P(1,0.337) = 0.563), 50ms after perturbation (P(1,0.872) = 0.353) and 100ms after perturbation (P(1,3.331) = 0.072). Significant differences between positions was found 150 ms after perturbation onset, well into the voluntary movement epoch (P(1,13.965) < 0.0005). As the muscle spindles in skeletal muscles code for position and velocity, lateral velocity was examined at the same temporal points. No significant difference between lateral velocity (P(1,0.606) = 0.438) was found at perturbation onset, while significant differences were found 50ms (P(1,5.565) = 0.021), 100ms (P(1,10.570) = 0.002), and 150ms (P(1,24.816) < 0.0005) after perturbation.

An overall comparison between perturbations yielded no significant differences in lateral positions (P(4,1.690) = 0.151) and lateral velocities (P(4,0.647) = 0.629) at perturbation onset, suggesting that for unperturbed and perturbed trials, participants were planning to reach straight between the obstacles to the end target.

Correlation analysis was made for TL and MMA with lateral position at perturbation onset (Figure 10). Correlation between TL and lateral position is significant R(89) = 0.120, p = 0.001; as well as correlation between MMA and lateral position, R(89) = 0.264, p = 0.011. For both measures, higher activation yields a more leftward position, which can be explained by the higher activation level of BB compared to TL, as can be observed in Figure 7.

Discussion

Lateral position, lateral velocity, and EMG activity of four elbow and shoulder muscles were measured to assess their influence in the online decision making after a mechanical perturbation during a reaching task. Lateral velocity dependence was observed 50ms after perturbation onset with no significant differences in lateral position or pre-perturbation muscle activity in the decision.

MMA was compared across the different time epochs before perturbation to see if muscle activation had any influence in the decisional process of avoiding obstacles by going in between or around them. Significant differences are found 145ms after perturbation, but a higher activity can be observed at perturbation onset and up until the voluntary epochs (Figure 8). Whereas not statistically significant, the small increase in muscular activity would result in an increase in joint impedance, minimizing the displacement caused by the force perturbation.

Analysis of the muscular activity in the TL shows that the first burst of muscle activity after perturbation occurred before 100ms. The timing of the reaction, before appearance of first voluntary bursts of EMG activity, would suggest that neural pathways and processes were engaged to launch this initial response.

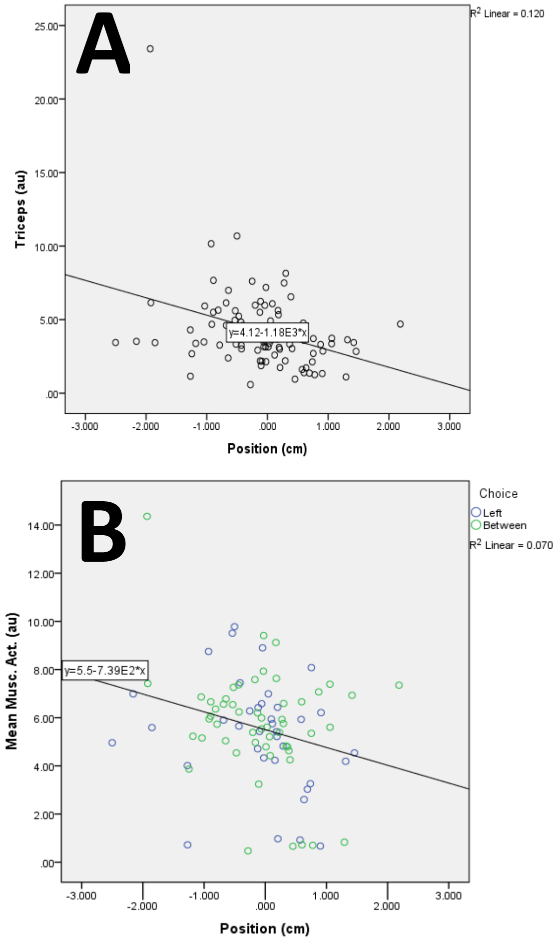


Figure 10. A. Correlation between Triceps pre-perturbation (-50 to 0 ms) and Position at perturbation onset. B. Correlation between MMA pre-perturbation (-50 to 0 ms) and Position at perturbation onset.

It was previously suggested (Nashed & Scott, 2014) that the decisional process to navigate between or around obstacles was dependent on lateral position at perturbation onset. Results of this study do not support this conclusion, as no differences in lateral positions (Figure 6 and Figure 9) was observed either before or during the first 100ms after perturbation onset. Significant differences in lateral position between the two strategies was found during the voluntary epoch, where the participant could consciously assess and react to the estimated position of the limb. However, it is important to point out that the results of this study do support the line of reasoning that lateral positions for trials that navigated between the obstacles tended to be more to the right than the position for trials that navigated around the obstacles.

Significant differences in lateral velocity was found between both strategies after 50ms, suggesting that strategy could have been chosen depending on this lateral velocity. The lower velocity for trials that navigated between the obstacles increased the muscular response to compensate the disturbance and correct the path to the end target. The velocity dependence of the choice of navigating between or around the obstacles would propose that the CNS can assess small changes in velocity better than position during movement. The inverse relation between lateral velocity of the hand and reflexive activity in the muscles, contrasts with a previous study that shows increased short and long latency responses with increased velocity (Dietz et al., 1994).

Simplification of MMA measure and reasoning

A previous study involving co-contraction used measures of tonic EMG and a measure of antagonist activation termed “wasted contraction” as an estimate of contraction levels in the limb (Gribble et al., 2003). Here the measure of mean muscle activity (MMA) in the limb was used, which represents the magnitude of normalized EMG activity across the opposing muscles of the limb. This increase in activity, regardless of its origin, would presume an increase in joint stiffness.

While useful as an approximation of increased muscle stiffness, the measure of MMA during the movement has some limitations. This calculation of muscle activity and MMA as an increase in joint stiffness is made using only surface EMG and does not consider the muscle moment arms or the contributions of the muscles not checked in this study. Furthermore, the dynamic properties of the limb are modified during movement, which can change the force-length and force-velocity relationships in the muscles, affecting EMG signals.

Limitations

There are three limitations that should be considered when interpreting the results of this study. First, it is possible that effects could have reached a statistical level of significance if more subjects had been tested. However, a small subject pool warrants that the effects seen are large, and therefore of greater practical significance. Second, the Haptic Master simulates a virtual mass, which the lower possible value that could be assigned was 2kg without the system vibrating uncontrollably. This increase in endpoint mass changes the internal feedforward model that the CNS has of the limb. While the participants were given a familiarization block before the experiments, control of limb movement could still be affected by this increase in mass. Lastly, more muscles regulate joint stiffness than those analyzed in this study. A more comprehensive study can involve analysis of more muscles in the arm.

Conclusion

Pre-perturbation activity of the muscles, lateral position and lateral velocity at perturbation of the limb does not modulate the decisional process of avoiding an obstacle in a reaching task after a mechanical perturbation. The decision-making process of avoiding obstacles in an environment is dependent on the velocity of the moving limb after a perturbation.

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Appendixes

Appendix A: Surface EMG Electrode Placement (Hermens et al., 1999)

Biceps brachii. Participants sat on a chair with the elbow flexed at a right angle and the dorsal side of the forearm in a horizontal downwards position. Electrode was placed on the line between the medial acromion and the fossa cubit at 1/3 from the fossa cubit. For the clinical test, a hand was placed under the elbow to cushion it from the pressure to then flex it slightly below a right angle, with the forearm in supination. Pressure was then applied against the forearm in the direction of extension.

Triceps brachii (Lateral head). Participants sat with the shoulder at approximately 90° abduction with the elbow 90° flexed and the palm of the hand pointing downwards. Electrode was placed at 50% on the line between the posterior crista of the acromion and the olecranon at 2 finger widths lateral to the line. For the clinical test, the elbow was extended while applying pressure to the forearm in the direction of flexion.

Pectoralis Major. Participants were asked to sit erect with their arms flexed 90° and with the palm of the hand facing inwards. Electrode was placed four fingers below the clavicle following the midclavicular line. For the clinical test, pressure was applied to the anteromedial surface of the arm, above the elbow in the direction of flexion.

Deltoid Posterior. Participants were asked to sit erect, with their arms hanging vertically and the palm of the hand pointing inwards. The electrode was then centered in the area about two finger widths posterior of the acromion. For the clinical test, a slight lateral rotation and slight flexion were entailed while pressure was applied against the posterolateral surface of the arm, above the elbow in the direction of adduction.