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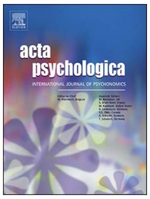

A method for measuring manual position control

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ABSTRACT

There is no generally accepted method for measuring manual position control. We developed a method for doing so. We asked university students to hold a handle that had one rotational degree of freedom. The angular position of the handle depended on the degree of pronation-supination of the forearm. The subjects' task was to hold the handle as steadily as possible to keep a needle positioned in a pie-shaped target zone on a computer screen. If the needle remained in the zone for 0.5 s, the gain of the feedback loop increased; otherwise the gain decreased or remained at the starting value of 1. Through this adaptive procedure, we estimated the maximum gain that could be achieved at each of the four pronation-supination angles we tested (thumb up, thumb down, thumb in, and thumb out) for each hand. Consistent with previous research on manual control, and so validating our measure, we found that our participants, all of whom were right-handed, were better able to maintain the needle in the target zone when they used the right hand than when they used the left hand and when they used midrange wrist postures (thumb up or in) rather than extreme wrist postures (thumb down or out). The method provides a valid test of manual position control and holds promise for addressing basic-research and practical questions.

1. Introduction

In many everyday tasks, it is important to hold one's hands steady. Think of a surgeon carrying out a delicate procedure, a welder striking and maintaining an arc on a precision machine, or a member of a bomb squad preparing to defuse a bomb. Given how important it is to maintain steady hand positions, it is surprising that there is no established method for determining how well hand positions can be maintained.

We pursued such a method here, focusing on the method's ability to pick up differences in manual positioning control for the two hands at different postures (at different pronation-supination angles). We were motivated to develop the method for applied as well as basic-science reasons. On the applied-science side, we thought such a measure could be used to indicate progress or lack thereof following stroke or injury given various drugs or rehabilitation regimens. We also thought the method might be useful in human-factors contexts such as tool design or personnel selection (e.g., who would make a good surgeon or bomb squad member). On the basic-science side, we thought the method could provide information about the degree of precision that is possible for different limb configurations and about the relative importance of visual feedback in judging and maintaining positions. The ensuing data could constrain future theorizing about motor control. For example, a theory like the one developed by the last author and others, which focuses on goal positions of the body and their suitability for different tasks (Rosenbaum, Loukopoulos, Meulenbroek, Vaughan, & Engelbrecht, 1995; Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001), could benefit from benchmark data about the stability of the postures that are proposed (cf. Solnik et al., 2013).

It was important to validate our method, so we focused on an aspect of position control that has been thoroughly studied before, namely, the degree of position control that can be achieved with the two hands and by each hand in different forearm pronation and supination positions. Previous knowledge about both of these aspects of manual control let us judge the validity of the measure obtained with our procedure.

With respect to the two hands, all of our subjects were right-handed, so we expected them to do better when using the right hand than the left. Obtaining that result would, in our view, constitute prima facie evidence that our method was valid.

With respect to pronation and supination, we expected our participants to do better if they had their thumbs facing up or inward (toward the midsagittal plane) than if they had their thumbs facing down

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or outward (away from the midsagittal plane). We based this expectation on several sources of evidence. First, the time to carry out aiming movements is shorter when the hand is in intermediate pronation-supination angles than when the hand is in extreme pronation-supination angles (Coelho, Studenka, & Rosenbaum, 2014; Hughes, Seegelke, & Schack, 2012; Rosenbaum, Chapman, Weigelt, Weiss, & van der Wel, 2012; Short & Cauraugh, 1999). Second, mechanical power is higher at intermediate pronation-supination angles than at extreme pronation-supination angles (Winters & Kleweno, 1993). Third, oscillation rates are higher at intermediate pronation-supination angles than at extreme pronation-supination angles (Rosenbaum, van Heugten, & Caldwell, 1996). Fourth and finally, hand positions are judged more comfortable at intermediate pronation-supination angles than at extreme pronation-supination angles (Rosenbaum et al., 2012; Rossetti, Meckler, & Prablanc, 1994; Solnik et al., 2013). Given these findings, we assumed that if we obtained evidence for better control at intermediate forearm angles, that would constitute further evidence for the validity of our approach.

2. Method

We asked our participants to grasp and hold a handle using their left or right hand in a range of orientations. The handle's orientation was reflected in the angular position of a needle appearing on a computer screen. The participant's task was to keep the needle within a narrow target range. Participants were asked to hold the handle as steadily as possible.

To probe the degree of control afforded by each manual posture, we dynamically altered the visuo-motor gain (i.e., the ratio of virtual object motion to actual object motion). If participants successfully maintained the needle within the target for 0.5 s, the gain increased and the needle became more sensitive to the handle's position. If participants were unable to maintain the needle within the target, the gain decreased or remained at the starting value of 1 and the needle became less sensitive to, or remained at the state of least sensitivity to, the handle's position. By manipulating the gain, we could magnify or minify the naturally occurring noise of wrist position vis a vis its visual depiction on the screen without changing any physical properties of the apparatus or visual display. Our main question was how high a level of gain participants could achieve for a given hand and hand position. We were interested in estimating the maximum gain, G_{MAX}, per hand and hand position so we could make statements about the relative degree of control that could be achieved by the hands in the positions they occupied. Our aim was not to find the optimal levels of control that could be achieved, but just to express the maximum level of control that could be reached as indexed by our maximum gain measure.

Behind the method were two main ideas. First, when visual feedback gain increases, greater control is needed to keep a visible cursor within a target of fixed width. By increasing the visual feedback gain and by identifying G_{MAX} for a given hand and hand-position, we could characterize the relative level of control that could be achieved as indexed by that variable. As stated before, but not expressed in terms of in G_{MAX} in particular, we now reiterate our prediction in terms of that variable. We predicted that G_{MAX} would be greater for the right hand than for the left hand and would be greater at midrange forearm orientations (up and in) than at extreme forearm orientations (down and out).

The second idea behind our method was to maximize sensitivity and minimize bias. If we had simply asked participants to do as well as possible at keeping the cursor in the target zone though the gain had a single unchanging value, our measure of performance might have been insensitive if the single gain were either too low or too high to differentially tax the neuromotor control system for the two hands and four hand positions. Regarding bias, participants might have entered the task biased by their beliefs or expectations and, with a single gain, their performance could have reflected those expectations or beliefs. We wanted to avoid a possible motivational confound of this kind. By dynamically changing the gain and by making the gain changes unobtrusive (another feature of our method, because nothing happened when the gain changed except for the relation between the handle's position and the needle's position on the screen), we could further reduce the chance that bias affected our results.

2.1. Subjects

Sixteen Penn State undergraduates (ten female, six male) participated in exchange for course credit. The subjects' ages ranged from 19 to 25 years (mean = 19.73 years, SD = 1.67 years). The subjects' mean height was 1.73 m (SD = 0.11 m) and their mean weight was 71.08 kg (SD = 22.82 kg). All participants reported preferring their right hand, as indicated in their responses to the short form of the Edinburgh Handedness Inventory (Oldfield, 1971). Their mean number of right-hand-preferred items out of 11 was 10.25. The study was approved by the Penn State Institutional Review Board.

2.2. Experimental setup and procedure

As shown in Fig. 1, the handle stood beneath a 95 cm high table on which rested a 48.3 cm diagonal screen with a resolution of

Fig. 1. Setup used in the experiment. Participants sat facing a computer screen. Here the needle (the black line extending from the central red dot) points straight up, indicating that the handle is at the middle of its acceptable range of motion. The red dot appearing in the upper left corner of the display indicates that the trial has not yet begun. The handle held by the participant is shown below the table. A clamp (bottom left) is affixed to the wheel on which the handle is mounted. The clamp was removed at the start of the trial. Here the handle is shown oriented vertically, allowing for "up" and "down" grasps. The handle could have also been oriented horizontally for "in" and "out" grasps. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

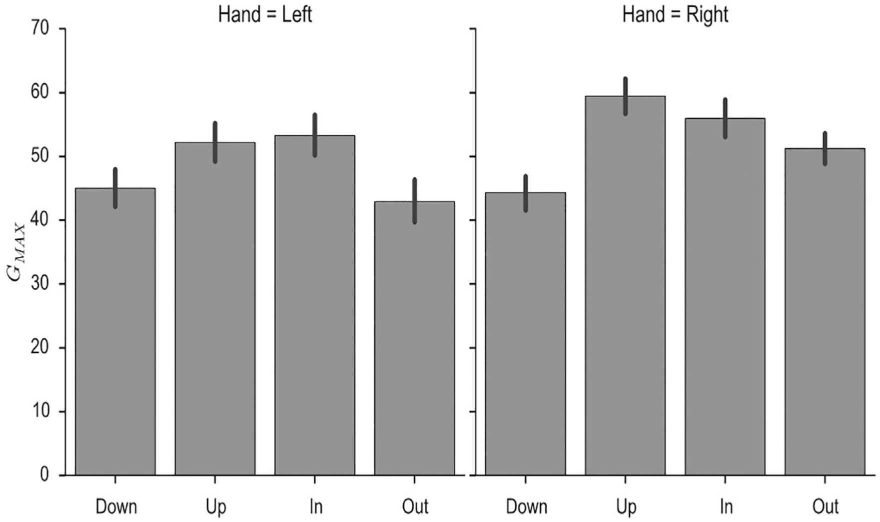

Fig. 2. Maximum gain, G_{MAX}, when the positioning task was performed with the left hand and right hand with the thumb (or the base of the thumb) pointing down, up, in (toward the midsagittal plane), or out (away from the midsagittal plane). The grey bars show the means over subjects. The black bars show the standard errors over subjects.

1440 × 900 pixels. The screen showed a blue circle with a green pie-shaped sector occupying 20° of the circle's area. A black line (the "needle") extended from the center of the circle to the outer edge of the circle. The line's orientation corresponded to the angular position of the handle, which was an 11.5 cm long metal drawer-type handle mounted on a 26.7 cm diameter aluminum wheel that turned with negligible friction.

The handle was mounted on a 60.9 cm high stool at the participant's midline and at or near the full extent of his or her reach. The participant adjusted his or her chair, as per instruction, to enable the reach. The front of the chair was parallel to the near edge of the table and was centered with respect to the handle apparatus and screen. The table occluded the participant's sight of the handle and his or her hand.

Each participant held the handle with the left or right hand, as per the instruction for that trial, at each of four target angles, "down", "in", "up", and "out" where "down" corresponded to the thumb-down position for each hand, "in" corresponded to the thumb-in position for each hand, "up" corresponded to the thumb-up position for each hand, and "out" corresponded to the thumb-out position for each hand. In this context, when we say "thumb" we mean the base of the thumb, or what is otherwise known as a radial grip (Keen, Lee, & Adolph, 2014). Participants held the handle with a power grip, as per instruction.

Before each trial, the handle was clamped so it stood either vertically for trials requiring down or up grasps, or horizontally for trials requiring in or out grasps. In all cases, the needle on the screen was initially centered within the target and was oriented toward the top of the circle. The clamping of the needle prior to the start of the trial ensured that participants started in the middle of the target sector at the onset of each 60 s trial.

Before the start of each trial, a red dot appeared in the upper left of the screen. Once the participant held the handle as per instruction, the experimenter, who was seated to the participant's left, reached over, released the clamp and pressed a key on a keyboard with his left hand to begin the trial. This caused the red dot to turn green, indicating that data collection was under way.

At the start of each trial, the gain (i.e., the ratio of needle angular displacement to handle angular displacement) was 1. After that, if the participant kept the needle within the target for 0.5 s, the gain was increased by 1, so if the gain had been 1, which meant that if a 1° of rotation of the handle was reflected in a 1 degree rotation of the needle, the new gain meant that a 1° of rotation of the handle was reflected in a 2 degree rotation of the needle. If the participant was unable to maintain the needle within the target for 0.5 s, the gain decreased by 1 if the gain was > 1; otherwise, it remained at 1. By manipulating the gain, we could amplify or attenuate the effects of the naturally occurring arm-position noise. This let us learn how well the participant could achieve the level of control corresponding to the gain being tested.

When the 60 s trial ended, the green dot in the upper left of the screen turned red and the experimenter told the participant to let go, return his or her hands to his or her lap, relax, and wait for instructions for the next trial.

Participants experienced two blocks of eight possible conditions (4 grasp positions × 2 hands), resulting in 16 trials per participant. Trials alternated between the right and left hands for each participant. Half the participants began with the right hand and half began with the left hand. All four orientations per hand were tested in a random order per participant before the four orientations were re-tested in another random order for the same participant with the other hand. Then, the four orientations were tested again for the same participant with the first hand s/he used, followed by the second hand s/he used.

The angular position data were collected using an Arduino™ microcontroller that measured wheel position using a U.S. Digital™ HD-25 Industrial optical encoder with 2500 pulses per revolution. Because the HD-25 was used as a true quadrature encoder, the total angular resolution was 10,000 counts per revolution, or an angular resolution of 0.036° of physical handle rotation. The Arduino™ microcontroller read the encoder pulses using digital interrupts and used an 115,200 kbps USB serial connection to stream the physical handle position to the desktop PC, which ran a Python™ program running at 200 Hz to record the handle position, needle position, current gain, and whether the needle was within the target sector. The needle position was updated at the screen's maximum refresh rate of 60 Hz.

3. Results

Fig. 2 shows the results for G_{MAX} grouped by *Hand* (left and right panels) and *Position* (the four values along the abscissa). All statistical tests were performed with R software (R Core Team, 2013) with the significance level set at $\alpha = 0.05$. When pairwise *t*-tests were performed, we used the Holm adjustment for multiple comparisons. We summarize the results before presenting the outcomes of the associated statistical tests.

Generally, participants achieved better control with the right hand than the left. G_{MAX} was higher for the right hand than for the left (52.7 ± 1.8 vs. 48.3 ± 2.1, respectively). Regarding the four grasp positions, participants did best in the up position, with the highest G_{MAX} (55.8 ± 2.7) when the base of the thumb was up, whereas participants did worst in the down position, with the lowest G_{MAX} (44.7 ± 2.4) when the thumb was down. This pattern was somewhat different for the two hands. For the right hand, the best control was achieved in the up position, with the highest G_{MAX} (59.4 ± 3.5) obtained with the thumb up, whereas control was worst for the down position, with the lowest G_{MAX} (44.3 ± 3.1) obtained with the thumb down. For the left hand, G_{MAX} was highest (53.2 ± 4.1) for the in position rather than the up position. The smallest (worst) values of G_{MAX} (42.9 ± 3.2) were obtained for the left hand when the base of the thumb pointed out.

Statistical analysis confirmed these statements. All p values associated with blocks, both for the block main effect and interactions of blocks with other factors, were > 0.3. There was a significant main effect of *Hand*, $F(1, 15) = 4.71$, $p = 0.046$, a significant main effect of *Position*, $F(3,45) = 8.42$, $p < 0.001$, while the interaction between these factors was not significant, $F(3,45) = 2.67$, $p = 0.058$. Post-hoc analysis revealed that G_{MAX} did not differ significantly between out and down or between up and in. The degrees of freedom for the analysis of variance results just presented were based on recommendations of Maxwell and Delaney (2004).

4. Discussion

In this study, we explored a method for measuring manual position control. We were motivated to develop such a method because we knew of no procedure that could provide a highly sensitive measure of this fundamental ability. The results we obtained fit with our expectations concerning hand differences and hand-position differences, so we view the outcome measure as valid.

The most novel feature of our method is its dynamic nature. The gain of the system being controlled changes dynamically according to the level of precision that is achieved. This allows us to probe the limits of people's manual positioning abilities. Had we left out this dynamic adjustment aspect, we might have picked up people's motivational states more than their actual manual positioning abilities. As indicated earlier, if, in effect, we had said to our subjects, “Hold your hand as steadily as possible,” they might have approached the task with eagerness or reluctance based on their beliefs about what they could or could not manage. Because our dynamic adjustment procedure occurred behind the scenes, as it were, the only direct visual feedback our subjects got was whether the needle was in the target zone. With this covert procedure, we were able to eliminate or greatly reduce the chance that bias would color our results. And because the gains we used spanned a wide range for each hand and hand position tested, our probe was more sensitive than it would have been if we had chosen a single fixed gain.

In the remainder of this discussion, we take up three further issues. First, we consider the relation of our approach to earlier findings pertaining to visuo-motor coordination. Second, we discuss the hand differences we found vis a vis an influential hypothesis that might have predicted a different result than the one we obtained. Third, we comment on future applications of our method.

4.1. Visuo-motor coordination

The gain manipulation we used was informed by previous research on visuo-motor control. The focus of this previous research was to understand how visual feedback is used for motor control and motor learning (e.g., Kagerer, Contreras-Vidal, & Stelmach, 1997). We are aware of only two studies that have exploited visuo-motor mappings to study wrist orientation. In one, Barra, Mégard, and Vidal (2013) asked participants to manually adjust the orientation of a three-dimensional virtual teapot under different gain conditions. In the other, Fernandes, Albert, and Kording (2011) asked participants to perform a task using a mobile phone application in which a ball appearing on the phone's screen could be moved to different positions by tilting the wrist to different orientations. The focus of these studies was the extent to which adaptation to changing visual feedback transferred across trials and angular excursions of the wrist. The degree to which some static wrist postures could be controlled relative to other positions was not tested, however.

Another study of visuo-motor coordination more directly inspired our approach. That study was by Langolf, Chaffin, and Foulke (1976), who invited participants to perform a reciprocal tapping task under a microscope. By having their subjects move a hand-held stylus back and forth between two targets as quickly as possible with amplified visual feedback, the experimenters forced very tiny movements. Via that gain increase, Langolf, Chaffin, and Foulke could show that perception was an important factor limiting the speed of aiming. For related results, see Fourneret and Jeannerod (1998).

We pursued similar logic here, using the gain of the system in our holding task to reveal differences in manual position control that we expected based on previous research. In particular, by adjusting the visual feedback gain during the maintenance of static postures, we managed to magnify effects of perception in the visuo-motor control system for a static positioning task, encouraging participants to use feedback to maintain precise error bounds on wrist position. Via this procedure, we could show that visual feedback plays an important role in manual positioning. We were also able to show that there are significant differences in manual positioning control achievable by the two hands in the positions we studied.

4.2. Hand differences

We found that the right hand was better than the left, as expected. This outcome was unsurprising considering that our subjects were all strongly right-handed. Still, it is worth mentioning that it was possible that we could have obtained the opposite result. We could have found that the left hand was better than the right hand, not just because this was logical possibility but also because of an influential hypothesis that might have predicted that outcome.

According to the dynamic dominance hypothesis of Sainburg (2005), the control of mechanical statics is better for the left hand than for the right hand, whereas the control of mechanical dynamics is better for the right hand than for the left. These claims of the dynamic dominance hypothesis explain why most of us hold our rice bowls with our left hands while using chop sticks with our right hands, why we hold our babies with our left arms while gathering nuts and berries with our right hands, and so on. Given that the task we studied here ostensibly required only the control of mechanical statics, we could have predicted, based on the dynamic dominance hypothesis, better performance for the left hand than for the right.

Does the ostensible conflict between our results and Sainburg's hypothesis invalidate the present method? By the same token, does it invalidate Sainburg's hypothesis? We think neither of these options must be chosen. On the contrary, we think the power of Sainburg's hypothesis provides a way of reaching a better understanding of our results. A way to reconcile our findings with Sainburg's hypothesis is to conceive of our task as one that placed demands both on statics and dynamics. Because of the large visual feedback gains that took effect near the end of each trial relative to the nominal case (gain = 1), we were able to encourage subjects to rely on visual feedback more when the gain was high than when it was low. When our subjects saw the needle leave the target zone, presumably due to small wrist movements caused by neuro-motor noise that would have gone unnoticed without magnification, they had to make corrections of the kind that have been studied in handle-rotation versions of the Fitts (1954) aiming task (Wright & Meyer, 1983). So our task didn't just require static control. It also required dynamic control. In that connection, it is relevant that other studies of visually guided aiming have shown that the efficiency of movement in the Fitts task is higher for the right hand than for the left in right-hand dominant subjects, as our subjects were (Vaughan, Barany, & Rios, 2012). Vaughan and colleagues concluded that the right hand is better at making controlled movements than the left hand is. The hand differences we observed agree with this conclusion.

Accordingly, our results can be seen as consistent with Sainburg's hypothesis, provided one views our task, as we now do, as one in which dynamics (correcting for error) played at least as important a role as statics (holding still).

4.3. Applications

We turn finally to possible applications of our method. As suggested earlier, our method can provide a sensitive measure of the degree of control that can be achieved by different effectors, by the same effector in different positions, and by different individuals performing in various conditions under precisely controlled magnification of the visuo-motor feedback gain.

We have already discussed the different effectors used here: the left hand and right hands. And we have discussed the different nominal positions that the effectors assumed: thumb down, thumb in, thumb up, and thumb out. But all these positions for both hands had the hands at a low position, beneath the table on which the screen stood. In future studies, each hand could be positioned at different heights and at different eccentricities to map out the degree of control that can be achieved in those different postures. Working with the hands in different parts of the workplace is a common challenge. Think of an auto or airplane mechanic reaching up to fix a part. For related work, see Wiker, Langolf, and Chaffin (1989) and Khan, O'Sullivan, and Gallwey (2009). The kind of handle we used could be placed at different heights and at different orientations and so could be held with the hand in a wide range of positions. In principle, the feedback could be auditory or tactile rather than visual if one wanted to study kinesthesis without regard to visual monitoring demands. However, as mentioned earlier, a carefully designed experiment using the sort of apparatus described here could also provide valuable insight about the relative importance of visual feedback when compared to musculoskeletal constraints and/or proprioceptive feedback, because the system allows precise specification of feedback gain and separate, precise measurements of both visual needle angle and actual handle angle.

Using the method with other populations is also an attractive possibility that has already been alluded to. Among the populations of interest would be elderly people. How and whether their position control improves given various treatments could be tracked.

The present method can also prove useful in the assessment of clinical problems where aging per se is not the agent of degeneration. Limb positioning may deteriorate as a result of stroke, neural or muscular degeneration, or other causes. By assessing the maximum control that can be achieved over the course of rehabilitation or as a function of which medication is being used, one could track improvement.

Finally, our method can be put to use in tool design. For example, in laparoscopic surgery, very delicate control of handheld instruments is needed. This has sparked debate about the optimal design for surgical tools (Berguer, 1998; Berguer, Forkey, & Smith, 1999; Van Veelen, Jakimowicz, & Kazemier, 2004). Modifying the handle on our apparatus to better match possible surgical-instrument designs could provide a direct test of the degree of control that can be achieved with alternative designs and a means by which the visual gain in such systems could be optimized. With the method we have developed, it should be possible to "get a better handle" on the handles used in everyday tasks and, more generally, to get a more detailed picture of manual positioning than has been possible before.

Author notes

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