Comparison of Dynamic (Effortful) Touch by Hand and Foot

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ABSTRACT. Spatial perception by dynamic touch is a well-documented capability of the hand and arm. Morphological and physiological characteristics of the foot and leg suggest that such a capability may not generalize to that putatively less dexterous limb. The authors examined length perception by dynamic touch in a task in which weighted aluminum rods were grasped by the hand and wielded about the wrist or secured to the foot and wielded about the ankle. Participants’ \( N = 10 \) upper and lower extremities were comparable in terms of (a) the accuracy and consistency of length perception and (b) their sensitivity to manipulations of the moments of the mass distribution of the rods. The authors discuss those results in terms of the field-like structure of the haptic perceptual system, an organization that may underlie what appears to be functional, rather than anatomical, specificity.

Key words: dynamic touch, foot, functional specificity, hand, perception

The haptic perceptual system is the means by which humans control their limbs, maneuver and manipulate objects, and come to know their properties (a sense often referred to as kinesthesis). The etymological root of words like maneuver and manipulate suggests that those are activities we expect to be conducted by hand. Words rooted in the foot, in contrast—at least those that do not concern locomotion—tend to be more passive or structural (e.g., pedigree, pedestal). Is that linguistic distinction anchored in the haptic system itself? More to the point, is the foot capable of detecting information about the objects it may manipulate?

Exploratory haptic behavior by hand and foot—so-called dynamic or effortful touch—is organized differently in terms of the parts of the anatomy that are recruited and how they are used. Receptors in the hand and foot have anatomically different morphological and physiological characteristics as well as different distribution densities. Skin properties (thickness of dermis and amount of adipose tissue), muscle properties (strength and stiffness), and patterns of motor and sensory innervations also differ (Kennedy & Inglis, 2002; Torgén & Swerup, 2002). Those anatomical differences are probably related to the observed differences in sensory acuity between the hand and foot. Despite some controversy, the results of most studies indicate that the hand is more sensitive for sensations of warmth (Hagander, Midani, Kuskowski, & Parry, 2000; Meier, Berde, DiCanzio, Zurakowski, & Sethna, 2001), vibration (Meier et al.), and touch sensibility (detecting Semmes–Weinstein monofilaments and discriminating two moving points; Kets, van Leerdam, van Brakel, Deville, & Bertelsmann, 1996). Conversely, the foot seems to be more sensitive to cold and pain (Hagander et al.; Meier et al.). In addition, between-participants variability for threshold sensation variables tends to be larger for the foot than for the hand (Bartlett, Stewart, Tambllyn, & Abrahamowicz, 1998; Hagander et al.). Moreover, the hand is associated with exploratory behavior at the small scale of the environment (so-called manipulatory spaces), whereas the foot is associated with exploratory behavior at the large scale of the environment (so-called ambulatory spaces; Lederman, Klatzky, Collins, & Wardell, 1987). Such differences, along with the larger volume of muscles possessed by the leg, may cause lower-extremity receptors to be better adapted to higher forces than are upper-extremity receptors (Torgén & Swerup). In sum, hand and foot present several anatomical and behav-

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ioral distinctions, suggesting that those appendages possess different haptic perceptual capabilities.

Individuals with compromised haptic perceptual systems provide a contrasting insight, however. Although the skin’s spatial acuity (e.g., Stevens, 1992; Thornbury & Mistretta, 1981) and vibratory sensitivity (e.g., Kenshalo, 1986; Schaumburg, Spencer, & Ochoa, 1983) are known to decline with age, presumably reflecting age-related changes in the distribution density and morphology of mechanoreceptors (e.g., Bolton, Winkelman, & Dyck, 1966; Cauna, 1965; Corso, 1981), perception of spatial extent by wielding is not similarly compromised (Carello, Thuot, & Turvey, 2000). Perhaps more surprising, an individual with an insensate hand and arm, who was unable to identify objects in the hand on the basis of active manipulation, was nonetheless able to discriminate the lengths of objects wielded by that hand (Carello, Kinsella-Shaw, Amazeen, & Turvey, 2006). In that context, it has been argued that wielding with the hand produces tissue deformation in the whole body, not just in the wielding limb, thereby allowing the individual to exploit the field-like structure of the mechanoreceptors (Turvey & Carello, 1995). That interpretation certainly suggests that wielding by the lower extremities could support successful spatial perception as well.

Establishing the haptic perceptual capabilities of the foot in healthy young adults requires groundwork. Fitzpatrick and McCloskey (1994) found that dynamic or effortful touch maintains upright posture through rotations around the ankles. Orientation perception and length perception were found to have a similar basis in the inertia tensor; thus, one might expect the lower extremities to be capable of perceiving other spatial properties, such as length. Our main goal in the present study was to use a task with well-established benchmarks for the haptic perceptual capabilities of the hand. Perception of the length of hand-held rods wielded about the wrist has been studied extensively and provides such a task. One can quantify and compare the success of perception by the two limbs by using measures of accuracy and reliability and by regressing perceptual judgments by the hand on judgments by the foot. An additional comparison index is made possible by the use of stimulus objects constructed from cylindrical rods with metal disks attached so that one can manipulate the object’s mass distribution independently of its length. In typical experiments using such objects, perceived length has been found to be related by a power function to the second moment of the mass distribution. In particular, perceived length scales to the maximum principal moment of inertia raised to the 1/3 power.1 For present purposes, therefore, we assessed whether length perception by the lower limb also shows dependence on moment of inertia and, if so, whether the exponent is the same.

We provided the parallel task for the lower extremity by placing the rod in a sleeve attached to the foot and allowing wielding about the ankle. The characterization of the mechanoreceptor substrate as field-like2 (Pagano, Fitzpatrick, & Turvey, 1993; Turvey & Carello, 1995), along with the success of individuals with deficits in that substrate, suggests that perceiving length by wielding about the ankle ought to parallel results for perceiving length by wielding about the wrist. It remains to be seen whether that capability may be compromised in the lower extremity simply because there is no tuning of the spatial capabilities of the lower limbs during everyday activities.

Method

Participants

Ten female undergraduate students (17–20 years of age) enrolled in Introductory Psychology at the University of Connecticut participated in partial fulfillment of a course requirement. Eight students had ipsilateral dominant limbs (6 were right-handed and right-footed, and 2 were left-handed and left-footed), whereas 2 had contralateral dominant limbs (both were right-handed and left-footed). We ascertained limb dominance by asking participants which hand they use for writing and which foot they use for kicking a soccer ball. The Institutional Review Board of the University of Connecticut approved the procedures.

Task, Apparatus, and Design

The objects to be wielded were aluminum rods (radius = 0.006 m) of three lengths. We manipulated the mass distribution of each rod by attaching to it an 0.15-kg cylinder at 50%, 70%, or 90% of its length measured from the proximal end. Table 1 provides rod lengths, masses, and corresponding values of a quantification of the mass distribution, namely, the principal moment of rotational inertia ($I_1$). For wielding by hand, we slipped the rod into a hollow plastic handle (0.14 m long, weighing 0.04 kg), flush with the end and secured with thumbscrews. For wielding by foot, we attached a slightly larger handle (0.21 m in length and weighing 0.06 kg) firmly to the foot (by sheathing the individual’s foot and shoe in plastic and taping the handle along the bottom, flush with the heel). The rod was again slipped into the handle, flush with the end, and secured with thumbscrews.3

When wielding with the hand (Figure 1A), the participant sat on a small chair facing an opaque black-felt curtain. The right hand was put through a hole in the curtain, with the forearm supported on an armrest and the wrist a few centimeters beyond the edge of the armrest (allowing free movement). The objects, which were always held with a full grip (i.e., the little finger positioned flush with the end of the rod and all four fingers wrapped tightly around the handle), were presented vertically. We instructed participants to use only wrist movements to wield the objects and to avoid contact with the curtain. Movement trajectories traced an inverted conical envelope. Participants provided judgments, in the form of magnitude productions, on a string and pulley system that was attached to a vertical column next to the

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Before each trial, we moved the marker to an initial position that was at the same height from the ground as the armrest, that is, at a position corresponding to the bottom of the rod. We told participants to move the marker up to the position where they perceived the end of the rod to be. No feedback was given on any of the trials.

When wielding with the foot (Figure 1B), participants sat on a large cushion on the floor. Both of their legs were supported as they extended under the curtain. The objects, which were securely affixed to the handle, were again presented vertically. We instructed participants not to bend their knees during the trials to ensure that their move-

<table>
<thead>
<tr>
<th>Length (m)</th>
<th>Mass (kg)</th>
<th>Mass position/Length</th>
<th>Wrist</th>
<th>Ankle</th>
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<tr>
<td>0.6</td>
<td>0.21</td>
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<td>0.9</td>
<td>0.224</td>
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Note. To calculate the moment of inertia \( I_1 \) of the wrist and the ankle, respectively, we took the average wrist-to-grasp distance to be 0.065 m and the average ankle-to-grasp distance to be 0.112 m.
ments were restricted to the ankle. Again, movement trajectories traced an inverted conical envelope. Perceptual reports were provided with the same pulley system as just noted. Before each trial, we moved the marker to an initial position that was at the same height from the ground as the participant’s heel, that is, at a position corresponding to the bottom of the rod (0.44 m lower than for wielding by hand). As before, we told participants to move the marker up to the position where they perceived the end of the rod to be.

All participants wielded with the hand and with the foot. Each of the nine rods was presented three times for each limb, yielding 54 trials per person. We blocked and counterbalanced the order of presentation of hand trials and foot trials over participants, and we randomized the order of the rods within each block. Before each block of trials, participants performed three practice trials to familiarize themselves with the task. The whole experiment lasted approximately 1 hr. There was a 2-min break between blocks.

Results

We compared performance by the foot with performance by the hand on a variety of dimensions. Those included (a) the reports of perceived length averaged over the three repetitions of each rod, (b) the consistency of the three reports to a given rod, (c) the accuracy of perceived length relative to actual length, and (d) the scaling of perceived length to moment of inertia. In a final comparison, we evaluated the relationship between perceived length by hand and by foot in terms of how well one predicted the other.

Perceived Length

We performed a 2 (limb) × 3 (rod length) × 3 (attached mass position) within-participants analysis of variance (ANOVA) on perceived length. The main effects of rod length, F(2, 18) = 95.74, p < .001, and mass position, F(2, 18) = 39.53, p < .001, indicated the standard pattern: Length judgments increased with actual rod length as well as with the distance of the attached mass from the rotation point (wrist or ankle). There was no main effect of limb, F(2, 18) = 1.65, p > .20, and no significant interactions involving limb, Limb × Length, F(2, 18) = 2.82, p > .08, or Limb × Mass position, F = 1. As can be seen in Figure 2, participants discriminated lengths by hand and by foot in a similar fashion and with a comparable influence of mass position.

Consistency and Accuracy

To assess the consistency or reliability of length judgments, we expressed as follows the average deviation of an individual’s responses as a percentage of that person’s mean perceived extent:

\[
\text{Reliability} = \frac{\sum_{i=1}^{N_o} \sum_{j=1}^{N_{rep}} \left| \frac{L_{p_{ij}} - \bar{L_p}}{L_p} \right|}{N_o \times N_{rep}} \times 100,
\]

where \(L_{p_{ij}}\) is the perceived length for object \(i\) on the \(j\)th trial, \(\bar{L_p}\) is the mean perceived length for object \(i\), \(N_o\) is the number of objects used in the experiment, and \(N_{rep}\) is the number of repetitions. A comparable measure of accuracy, expressed as a percentage of actual extent \((L_a)\), is provided by mean root square (MRS) error:

\[
\text{MRS} = \frac{\sum_{i=1}^{N_o} \sum_{j=1}^{N_{rep}} (L_{p_{ij}} - L_a)^2}{N_o \times N_{rep}} \times 100.
\]

We obtained two reliability measures and two MRS measures for each participant, one for perceived length by hand and one for perceived length by foot. Those measures allowed not only a comparison of performance by the two limbs but also an indication of whether systematic error, captured by MRS, reflects a distortion over and above random fluctuation, captured by reliability (Norman, Todd, Perotti, & Tittle, 1996). If a perceiver is as likely to underestimate as to overestimate, then that is simply random fluctuation. But if a perceiver is drawn consistently away from the actual magnitude—as if he or she were using a different ruler—then that is systematic error. In the present case, we expected systematic error to be larger than random fluctuation because the ruler being used by perceivers...
was fashioned from the objects’ mass distributions rather than their lengths.

A 2 (limb) × 2 (reliability vs. MRS) within-participants ANOVA revealed a main effect of analysis, $F(1, 9) = 18.77$, $p < .002$, but we found neither an effect of limb nor an interaction between analysis and limb, both $Fs < 1$. MRS averaged 27.0% for judgments by hand and 27.0% for judgments by foot. Reliability averaged 8.1% for judgments by hand and 10.0% for judgments by foot. The values for both measures compare favorably with those obtained in handheld wielding by young adults (cf. Carello, Thuot, Andersen, & Turvey, 1999). The difference between reliability and MRS indicated systematic error.

**Inertial Scaling**

We conducted regressions of log perceived length on log $I_1$ for both limbs. Recall that the typical exponent of a power function so obtained is 1/3. The regression analyses revealed a significant dependence on $I_1$ for both limbs. For the hand, the regressions were significant for all participants. The value of $r^2$ ranged from .75 to .97, with a mean of .89. For the foot, the regressions were significant for all but 1 participant ($r^2 = .38$, $p < .08$). The value of $r^2$ otherwise ranged from .71 to .92, with a mean of .83. An ANOVA conducted on the $z$ transformations of $r^2$ values for all participants revealed a difference between hand and foot, $F(1, 9) = 9.27$, $p < .01$. The slopes of the regressions did not differ significantly for the two limbs, $F < 1$. For the hand, the slopes ranged from .16 to .55, with a mean of .37; for the foot, the slopes ranged from .07 to .67, with a mean of .32. Finally, the intercepts were not distinct for the two limbs, $F < 1$. For the hand, the intercept antilogs ranged from 1.00 to 1.95, with a mean of 1.43; for the foot, the intercept antilogs ranged from 0.64 to 2.26, with a mean of 1.41.

**Foot–Hand Regressions**

One more comparison, borrowed from the domain of aging research, is instructive. Researchers commonly use Brinley plots (Brinley, 1965) to assess the predictability of reaction times in one age group on the basis of reaction times in another age group. Linearity of such a plot suggests a common mechanism for perception by the two groups (Salthouse, 1991). In the present case, linearity of a foot–hand plot would indicate that the two limbs do not differ qualitatively with respect to length perception by dynamic touch—the perceptual performance by either limb could be predicted from that of the other limb. As is evident in Figure 3, the foot–hand plot is, indeed, linear ($r^2 = .96$). The individual linear regressions were significant for 9 of 10 participants. The average slope of .73 was significantly different from 1.0, $t(9) = -3.6$, $p < .01$. A shallow slope may indicate that the rods are more discriminable by hand than by foot. It should be noted that a similar comparison of the dominant and nondominant hands revealed that the slope (with a mean of .86) also differed significantly from a slope of 1.0 (Carello et al., 2006).

**Discussion**

Manual exploratory activities such as wielding and hefting have been the focus in research on dynamic (effortful) touch. Very little attention has been devoted to perceptual capabilities of lower limbs. In the present contribution, we sought to explore and compare the perceptual capabilities of feet and hands. Results showed that perception of spatial extent by the foot and by the hand are comparable on several dimensions: the accuracy of responses, the consistency of responses, and the physical constraint on those responses. This commonality was reinforced by the linearity of foot–hand regressions.

The degree of equivalence is, perhaps, surprising in light of certain psychophysical facts that point to differences in the sensory capabilities of hand and foot. Sensory discrimination and haptic perception need not be interdependent, however. Sensory discrimination is about the state of the physiology; haptic perception is about the information specifying object properties. That is why spatial perception by dynamic touch generalizes to a variety of grips, for example overhead and underhand grips (Solomon, Turvey, & Burton, 1989); pinch grip (Pagano, Kinsella-Shaw, Cassidy, & Turvey, 1994; Santana & Carello, 1999; Turvey, Park, Dumais, & Carello, 1998); movement frequencies (Solomon & Turvey, 1988); movement magnitudes (Pagano et al., 1993; Solomon & Turvey; Stroop, Turvey, Fitzpatrick, & Carello, 2000); tissue contacts, for example, a single hand, a hand and a knee, the bottom of one hand and top of the other (Carello, Fitzpatrick, Domaniewicz, Chan, & Turvey, 1992); a probe rod to lift the target rod (Peck, Jeffers, Carello, & Turvey, 1996); and participant populations, for example, young adults, the elderly (Carello et al., 2000),
and an individual with an insensate limb (Carello et al., 2006). The main distinction seems to be captured by the local effects of psychophysical tests of sensitivity and the global effects of perceptual tasks in which different parts of the haptic system (e.g., hands, feet) and the environment (e.g., tools) appear to be recruited under different circumstances to perform the same function.

Logical arguments for the relevance of moments of mass distribution to constraining perception by effortful touch suggest that the reliance on $I_1$ for perceiving length by foot is, perhaps, not so surprising. $I_1$ is a variable that the muscle sense can detect. Even though the particulars of the mechanoreceptive substrate may differ across the body, the nature of the variables that can influence that substrate need not differ. Differences in accuracy and consistency might be expected, however, because of the perceptual tuning of the upper limbs during everyday activities. Many activities using the hands rely upon—and, one may imagine, promote—spatial capabilities (e.g., consider the use of implements in cooking, construction, and sports). Once again, the data from experiments on dynamic touch should have tempered that expectation. Although the two hands may be expected to differ in their relative expertise, the spatial capabilities of the dominant and nondominant hands are comparable (Carello et al., 2006). Moreover, expert tennis players do not enjoy an advantage over novices in perceiving either the lengths or the preferred striking locations of rods or rackets (Carello et al., 1999).

The design of the haptic perceptual system allows successful control of action under a variety of circumstances, whether defined by tissue or environment. Despite obvious differences in sensory physiology, psychophysical achievements, and putative expertise for different participant groups and different limbs, the haptic perceptual system as a whole seems to exhibit functional specificity. It reconfigures itself to perform a given task effectively. The meaningful division of labor for the haptic system seems to be in terms of particular tasks, not anatomical units, tools, ages, or levels of expertise. Different parts of the body are capable of temporary, or soft, assembly (Kugler & Turvey, 1987) to perform the same task. That interpretation is consistent with a characterization of the haptic system as a smart perceptual device (Carello et al., 1992; cf. Runeson, 1977) that can recruit different anatomical components to obtain a single goal.

Are performances by the two limbs truly equivalent? The only differences we detected were quite subtle: The tightness of the fit to $I_1$ was higher for hand than for foot, and the slope of the foot–hand regressions was significantly less than 1.0. In contrast, for one common clinical metric, one must find a difference of two standard deviations before one can conclude that a unilateral injury has compromised the sensory capabilities of one limb in comparison with those of its unaffected counterpart (Kemler, Schouten, & Gracely, 2000), in effect, using one limb as a control for the other. It should also be noted that the slope of the Brinley plot has the same sort of difference that distinguishes performances by the dominant and the nondominant hands (Carello et al., 2006). In that regard, it has been argued that the two hands do not differ so much in the routine superiority of the dominant hand at controlling actions but in the respective specializations of the two hands, that is, a simple division of labor in human skilled bimanual action (Guiraud, 1987). For example, the dominant hand may be better at fine-grained manipulation, but the nondominant hand is better at coarser-grained stabilization, and both roles are needed if one is to accomplish a task (e.g., cutting paper with scissors). That characterization reflects the functional character of perception.

A functional characterization may also reflect the poverty of a label such as length for a to-be-perceived property. Length is really a place holder for something like reachable with one hand (foot) so as to do x. In that context, the controllability of actions by the two limbs may indeed differ, and that should show up in perception. What the hand can do with an object will differ from what the foot can do with that same object. With an appropriately functional question, that difference will emerge. However, our point in the present research remains that the lower limbs are capable of spatial perception of surprising accuracy and consistency.

**ACKNOWLEDGMENT**

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**NOTES**

1. There is a debate in the literature as to whether the mechanical constraint is the first moment or the second moment (cf. Kingma, Beek, & van Dieën, 2002; Stroop et al., 2000). Those quantities are highly correlated for the present objects. We used the second moment because it provided a specific exponent that enabled us to characterize the mapping to perceived length.

2. The mechanoreceptor population in the joints and tendons is the anatomical support for dynamic touch. It submits to a mathematical description based on fields constituted by tissue deformations that exhibit different pressure sensitivity in different directions.

3. For hand-held rods, we defined the principal moment of inertia, $I_1$, around a rotation point in the wrist. We took the location of that point to be, on average, 0.04 m along a rod’s long axis from the proximal end and at a perpendicular distance of 0.07 m from the rod’s long axis. For rods secured to the foot, we defined $I_1$ around a rotation point in the ankle. The location of that point was taken to be, on average, 0.07 m along a rod’s long axis from the proximal end and at a perpendicular distance of 0.11 m from the rod’s long axis. (For calculation conventions, see Stroop et al., 2000.) The shoe was not included in the calculations, following the convention of Pagano et al. (1993), who omitted an attached splint from their reported calculations. Length perception was identical both with and without the attached splint, suggesting that the inertia of a “worn object” does not influence the perception of the target object (C. Pagano, personal communication, June 23, 2006).

4. In contrast with the standard RMS, in which the deviations of perceived length from actual length are summed before taking the root, the benefit of MRS is that it scales the error as a dimensionless Weber fraction (and functions, therefore, like the reliability measure). The standard RMS is not invariant over different units of measurement and, in consequence, is more difficult to interpret. RMS and MRS are linearly correlated.
5. We did not record rod movements, so they may have differed in magnitude or frequency for the two limbs. One could conjecture that larger movements by foot may have compensated for an otherwise diminished discriminative ability. However, such differences have not mattered to length discrimination by the upper limb. Perceived length was equivalent under manipulations of frequency of wielding (Solomon & Turvey, 1988, Experiment 4) and variation in angular excursion because of wielding about the wrist, elbow, or shoulder (Pagano et al., 1993). Moreover, a comparison of free wielding and static holding revealed no difference in reliability or accuracy (Stroop et al., 2000).

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