Task difficulty and inertial properties of hand-held tools: An assessment of their concurrent effects on precision aiming

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Abstract
Aiming hand-held tools at targets in space entails adjustments in the dynamical organization of aiming patterns according to the required precision. We asked whether and how these adjustments are modified by the tool's mass distribution. Twelve participants performed reciprocal aiming movements with a 50-cm long wooden probe. Kinematic patterns of probe movements were used as a window into the behavioral dynamic underlying performance of a reciprocal aiming task. We crossed three levels of task difficulty (IDs 2.8, 4.5 and 6.1) with two types of probe varying in their mass distribution (proximal vs distal loading). Movement duration was affected by task difficulty and probe loading (shorter for larger targets and proximal probe loading). Progressive deviations from a sinusoidal movement pattern were observed as task difficulty increased. Such deviations were more pronounced with proximal probe loading. Results point to a higher degree of non-linearity in aiming dynamics when the probe was loaded proximally, which might reflect employment of additional perceptual-motor processes to control the position of its less stable tip at the vicinity of the targets. More generally, the effects of probe loading on aiming pattern and dynamics suggest that perceptual-motor processes responding to task level constraints are sensitive to, and not independent from, biomechanical, end-effector constraints.

1. Introduction
Numerous daily and sports activities involve aiming the distal end of a hand-held tool or implement to targets in space. Driving a nail into the wall with a hammer or placing a screwdriver onto a screw head are but two representative examples. When performing any of these activities, a skillful actor patterns his or her muscular forces to control the motions of the end-effector (here the hand-held object) so as to achieve the intended target-object relation. Task-specific use of hand-held tools and implements therefore requires sensitivity to constraints at the level of the task (e.g., accuracy requirements) and constraints at the level of the end-effector (e.g., mechanical properties of the tool or implement being used). In the present contribution, we examined the concurrent influences of both types of constraints on the performance and kinematics of precision aiming, which is a fundamental component of the functional use of hand-held objects.
Inspired by the seminal work of Woodworth (1899) and Fitts (1954), Fitts and Peterson (1964), the effects of task constraints have been extensively explored in goal-directed aiming (see Plamondon & Alimi, 1997, and Elliot, Helsen, & Chua, 2001 for reviews). Both the duration and the kinematic pattern of a successful aiming movement have been demonstrated to vary as a function of a task index of difficulty (ID) combining the distance D to be covered and the tolerance for terminal spatial variability delimited by target width W. The relation between task difficulty – with $ID = \log_2(2D/W)$ being the most commonly used form – and movement time (MT) is in fact so robust, in both the discrete and reciprocal versions of Fitts' paradigmatic aiming task, that it has

come to be known as Fitts' law.

The lengthening of MT observed when the aiming task becomes more difficult has been related to systematic changes in the kinematic pattern of aiming movements, in both the discrete (e.g., Beggs & Howarth, 1970; Elliott, Helsen, & Chua, 2001; MacKenzie, Marteniuk, Dugas, Liske, & Eickmeier, 1987) and reciprocal (e.g., Guiard, 1993; Huys, Fernandez, Bootsma, & Jirsa, 2010; Mottet & Bootsma, 1999) versions of the task. When task difficulty is low (i.e., when aiming for relatively large targets) movement patterns demonstrate symmetrically-shaped velocity profiles. Movements performed under higher levels of task difficulty are characterized by a progressive asymmetry in the velocity profile, mainly due to a lengthening (both in absolute and relative terms) of the duration of the deceleration phase. The window into the perceptual-motor processes underlying task execution offered by analysis of the characteristics of the kinematic patterns is perhaps richest for Fitts's (1954) reciprocal version of the aiming task, as portraying the to-and-fro movements into phase and Hooke spaces provides insight into the underlying dynamics (Bongers, Fernandez, & Bootsma, 2009; Bootsma, Fernandez, & Mottet, 2004; Bootsma & Mottet, 2004; Bootsma, Mottet, & Zaal, 1998; Buchanan, Park, & Shea, 2004; Buchanan, Park, & Shea, 2006; Fernandez & Bootsma, 2004; Fernandez & Bootsma, 2008; Guiard, 1993; Mottet & Bootsma, 1999; Mottet, Guiard, Ferrand, & Bootsma, 2001).

Geometrical and mechanical characteristics of the end-effector have also been demonstrated to affect the time requiredto perform an aiming movement. For a given level of task difficulty, increasing the length of a hand-held probe (Baird, Hoffmann, & Drury, 2002) and increasing the mass transported (Fernandez& Bootsma, 2004; Fitts, 1954; Hoffmann, 1995; Hoffmann & Hui, 2010; Konz & Rode, 1972; Langolf, Chaffin, & Foulke, 1976) both give rise to a lengthening of MT. Most of these studies focused exclusively on MT and did not address the kinematic patterning of the aiming movements. One exception is the study performed by Fernandez and Bootsma (2004). These authors exploited the anisotropy of the arm's workspace to investigate the effect of total transported mass through manipulations of the direction of end-effector motion during a reciprocal aiming task. Results showed that, at each level of task difficulty (IDs of 3, 4, and 5), the duration of movement increased when participants moved in directions associated with higher magnitudes of transported mass. For example, movement time was longer when transport of the entire upper limb was required to move between targets than when only transport of the less massive forearm was required. Importantly, manipulations of total transported mass did not provoke changes in the movement's kinematic patterns. In particular, no changes in the harmonicity of aiming patterns or in the underlying dynamical organization were observed. From these results they concluded that while (informational) constraints at the level of the task affected the processes underlying movement organization, (biomechanical) constraints at the level of the effector did not.

In the present study, we explored the effects of mass distribution along a long-shafted probe on the duration and organization of reciprocal aiming movements. The mass distribution of a hand-held object can, in principle, affect its appropriateness for performing manual tasks, and hence, influence the organization of aiming movements. For example, by the laws of mechanics, a hammer (whose mass is concentrated far from the point of grasp) is effective for transferring momentum to an external target, minimizing the need for generating muscular torque. However, maneuvering the hammer to adjust the position of its weighted end is relatively hard, particularly when the task involves high accelerations. Designing hammers with large heads is a strategy to compensate for the low maneuverability of the hammer's end position when hitting the typically very small nail heads. In contrast, by virtue of its mass being concentrated closer to the point of grasp, a screwdriver is comparatively ineffective for transferring momentum, but less difficult to maneuver. Maneuverability would be particularly beneficial for precision tasks requiring high speeds and rapid adjustments in end-effector's acceleration pattern. Here we arrive at the main hypothesis of the present experiment: tools with their mass concentrated close to point of grasp are expected to allow adjustments in the underlying perceptual-motor organization that minimize declines in performance (speed) as precision demands increase. We therefore expect that, differently from manipulation of transported mass, manipulation of a probe's mass distribution will affect not only the duration of aiming movements but also their kinematic pattern, particularly when accuracy demands are more stringent. Confirmation of this hypothesis would push a reassessment of the current view that task level constraints are informational while biomechanical constraints are not.

Recently, Lin and Chen (2014) have studied the effect of mass distribution of long-shafted probes on the duration of aiming movements. No difference in movement time was observed when proximal and distal loading conditions were compared though middle loading was associated with faster performance). The authors suggested that distal and proximal loading benefit different aspects of aiming movements, leading to a similar effects on global performance. However, these authors did not address the kinematic patterning of the aiming movements and, therefore, the effect of end-effector's mass distribution on the perceptual-motor processes supporting aiming tasks remains unknown. Accordingly, in the present contribution we evaluated the concurrent effects of task difficulty and asymmetric loading of a hand-held probe on (a) performance of a reciprocal aiming task (in terms of MT), and (b) kinematic patterns of end-effector movements supporting such performance.

2. Method

2.1 Participants

Twelve right-handed volunteers (2 male and 10 female), ranging in age from 19.9 to 26.9 years (M ± SD = 23.5 ± 2.5 years) participated in the study. All participants reported normal or corrected to normal vision and had no neuro-musculoskeletal conditions that could interfere with their performance of the experimental task. Participants provided their informed consent prior to inclusion in the study, which was approved by the local ethics committee.

2.2 Task and materials

Participants were asked to tap the distal point of a long-shafted probe between two targets as fast and as accurately as possible. The probe's shaft consisted of a cylindrical wooden rod (length = 50 cm; diameter = 1 cm; mass = 50 g). The mass distribution of the rod (and, hence, the probe's appropriateness for the experimental task) was manipulated using a steel cylinder (length = 7 cm; mass = 140 g) that was firmly attached to the rod at either 10 or 40 cm from its point of grasp. This manipulation effectively created two different probes (P_{Wprox} and P_{Wdist}) of equal length, diameter and mass, but with different maximal principal moments of inertia (P_{Wprox} = 63.1 g cm2; P_{Wdist} = 273.1 g cm2). P_{Wdist} is more difficult to maneuver by virtue of its higher concentration of mass far from the hand, which is most simply reflected in a higher magnitude of I (see Hove, Riley, & Shockley, 2006). Following the same line of reasoning, P_{Wprox} is less difficult to maneuver.

Three equally-sized (50 by 15 cm) target boards were constructed from ethylene-vinyl acetate. In each board, two circular targets were positioned at a center-to-center distance D of 35 cm. The three boards differed with respect to the diameter representing width W of the targets (W = 1, 3 and 10 cm), which were selected to obtain three levels of task difficulty. Combinations of W and D gave rise to task ID's of 6.1, 4.5, 2.8 (hereafter referred to as $ID_{6.1}$, $ID_{4.5}$, $ID_{2.8}$).

A passive marker attached to the probe's distal end allowed sampling of the probe's position at a rate of 200 Hz using a three-camera ProReflex video-based motion analysis system (Qualisys Medical AB, Gothenburg, Sweden). The system was calibrated before each session, with maximal accepted residual error of 0.5 mm.

2.3 Procedure

For performance of the reciprocal aiming task, participants stood facing a table of adjustable height. For each trial one of the three target boards was firmly attached to the table top. The boards were positioned according to pre-set markers to guarantee that the location of the centers of the targets remained the same for all task IDs. The height of the table was adjusted such that participants would be able to maintain their upper arm along the side of the body and the forearm at about 90° at the elbow joint during performance of the task that required medial-lateral movements. Prior to the experiment proper, participants had approximately 10 min of practice in order to ensure understanding of task requirements. They practiced with the three ID's, starting with the lowest, followed by the intermediate and the highest. For the practice trials participants used the wooden probe designed for the experiment with no load attached to it. During the familiarization phase, participants selected a comfortable base of support for task performance and an experimenter marked the position of their feet. This procedure assured the same position of the participant with respect to the targets for all experimental conditions.

Before each experimental trial, participants were properly positioned and handed one of the two probes. They grasped the probe so that its proximal end was flush with the bottom of the hand. Participants then performed the reciprocal aiming task after the experimenter had started data collection by the motion analysis system. Each valid trial consisted of a sequence of 25 successful aiming movements. If participants missed a target, they were asked to repeat the trial and the previous was discarded. Four participants had to repeat trials. Each of these participants repeated 3 to 4 trials for the highest ID condition.

There were six task conditions (two probe types crossed with three task ID's). The participants performed each condition twice, totaling 12 fully randomized trials. Participants were allowed to rest between trials as needed.

2.4 Data reduction and analysis

Guided by the task dynamic approach, we assume that the action system exploits limit cycle dynamics to produce self-sustained, rhythmic precision aiming motions with frequency and stability adapted according to extant task constraints (Mottet & Bootsma, 1999; Saltzman & Kelso 1987). We were interested in understanding whether biomechanical constraints (in particular end-effector mass distribution) affect the period of oscillations and most importantly whether such effects are related to changes in the dynamical regime producing the oscillations. Movement time (i.e., half-cycle duration) was used as an index of global performance of the aiming task while

the kinematics of aiming movements were used as a window into the underlying dynamical regime. According to the task dynamic approach, the underlying dynamical organization of goal-directed rhythmic movements (the focus of the present contribution) can be appropriately captured in a one-dimensional task space—in this case the task's main axis, linking one target center to the other (Saltzman & Kelso 1987). Therefore, for all analyses described below, we have used position time series of the probe, in the latero-lateral axis[1].
All position time series were filtered using a dual-pass second-order Butterworth filter with a cut-off frequency of 5 Hz. Velocity and acceleration time series were subsequently derived using a 3-point central difference technique. Each trial was segmented into individual (half-cycle) aiming movements based on peaks and valleys in the position signal corresponding to zero-crossings in the velocity signal. In order to minimize the chances of including transient performance the first three and last two aiming movements were discarded. For each trial, analysis thus concerned 20 aiming movements.

2.4.1 Movement time

MT was defined as the mean half-cycle time, that is, the mean time it took participants to move from one target to the other (Fitts, 1954). MT was calculated (for each condition performed by each participant) as the average time between two consecutive reversals of movement direction.

2.4.2 *Kinematic patterns*

The movement of the probe between targets in each trial was summarized in an average normalized cycle (Fernandez & Bootsma, 2004; Fernandez & Bootsma, 2008; Mottet & Bootsma, 1999). To this end, the 10 left-to-right and the 10 right-toleft movements were first averaged at constant phases of the movement (21 points, using steps of 5% MT) for position, velocity, and acceleration. The resulting time-series were then normalized to render their scales comparable over conditions. This was achieved by dividing the position, velocity and acceleration time-series, respectively, by A, Ax and Ax2, with A defined as mean maximal deviation from the center of oscillation and x as the mean frequency of motion (defined by 2p over mean trial period or 2 MT). The average normalized cycle was obtained by combining the back-and-forth average normalized half-cycles.
To characterize the patterns of motion produced in each experimental condition, we portrayed the between-participant average normalized cycles in phase space (velocity as a function of position; cf Mottet & Bootsma, 1999) and Hooke space (acceleration as a function of position; cf Guiard, 1993; Mottet & Bootsma, 1999). The degree of asymmetry in acceleration and deceleration phases of aiming movements is reflected in the (a) off-center location of the peak velocities in the phase portrait; and (b) the off-center location of the zero crossings in acceleration in the Hooke portrait (Mottet & Bootsma, 2001). Inspection of phase and Hooke's portraits also allowed an evaluation of the dynamical organization of the perceptualmotor system supporting task performance. As previously noted, we assumed that the action system exploits limit cycle oscillation dynamics to produce self-sustained rhythmic movements in an abstract task space (Saltzman & Kelso 1987). We further assume that analysis of aiming trajectories on phase and Hooke's portraits can reveal the underlying processes, both dissipative (energy-related) and conservative (stiffness-related), supporting production of aiming movements (Beek & Beek, 1988; Mottet & Bootsma, 1999). The type of non-linearity characterizing the operative dissipative and conservative processes and the magnitude of their contribution to task performance are revealed respectively in the deviations from a perfect circle in phase space and in the deviations from a straight line in Hooke space. The particular types of nonlinearities and their contribution to task dynamics depends on the desired end-product: here a reciprocal aiming movement satisfying task and biomechanical constraints.
To quantify the qualitative changes in the movement patterns associated with changes in the underlying dynamical organization, we calculated for each aiming movement the normalized peak acceleration (NPA, Fernandez & Bootsma, 2004), by dividing the observed peak acceleration by Ax2, where A corresponds to half the distance between movement extremes andx to p over the aiming movement's (half-cycle) duration. NPA for each trial was then obtained by averaging the individual values for the 20 aiming movements (half-cycles). With Ax2 corresponding the peak acceleration of a sinusoidal movement of amplitude A and frequency x, a movement governed by a linear dynamics gives rise to a NPA value of 1. Progressive deviations of NPA from 1 index progressive deviations from a sinusoidal movement pattern, signaling the progressively stronger contributions of non-linear processes to the performance of aiming movements.

2.5 Statistical analysis

For each dependent measure (MT and NPA), the results were averaged across the two trials of each condition

[1] It is conceivable that physical contact of the pointer with the target could affect the pointer's motion in the horizontal plane close to the target. There is, however, no evidence of such effects in the data, which reinforces the pertinence of our choice of restricting analysis to the one-dimensional task space.

and 2 x 3 repeated-measures analysis of variance (ANOVA) was conducted. The independent variables were the probe's functional appropriateness operationalized by the mass distribution of each probe type (P_{Wprox} and P_{Wdist}) and the accuracy demands of the task operationalized by task ID (2.8, 4.5 and 6.1).

3. Results

3.1 Movement time

The 2 x 3 ANOVA performed on MT demonstrated significant main effects of Task ID [$F(2, 22) = 82.49$; $p < 0.001$, $\eta_p^2 = 0.88$] and Probe Type [$F(1, 11) = 37.59$; $p < 0.001$, $\eta_p^2 = 0.77$]. The analysis also showed a significant Task ID x Probe Type interaction [$F(2, 22) = 6.87$; $p < 0.01$, $\eta_p^2 = 0.39$]. As can be seen from Fig. 1 and confirmed by contrast analyses, for each type of probe MT increased with task ID (p's < 0.001). Moreover, probe type affected MT at each level of ID (*p*'s < 0.001), with P_{Wprox} (easier to maneuver) associated with shorter MTs than P_{Wdis}. While MT was thus shorter when the task was performed with P_{Wprox} across all levels of difficulty, the interaction indicated that the difference between probe types increased with increasing task ID (see Fig. 1).

3.2 Kinematic patterns

The 2 x 3 ANOVA performed on NPA demonstrated significant main effects of Task ID [$F(2, 22) = 39.09$; $p < 0.001$, $\eta_p^2 = 0.78$] and Probe Type [$F(2, 22) = 15.34$; $p < 0.001$, $\eta_p^2 = 0.58$], as well as a significant Task ID x Probe Type interaction [$F(2, 22) = 18.03$; $p < 0.001$, $\eta_p^2 = 0.62$]. As can be seen from Fig. 2 and confirmed by contrast analysis, for each type of probe NPA increased with task ID (all ps < 0.001), indicating an increasing deviation of aiming movements from a perfectly sinusoidal pattern as the level of task difficulty increased. Contrast analysis also demonstrated that probe type only affected NPA at the highest ID (p < 0.001), with P_{Wdist} (more difficult to maneuver) showing a smaller NPA than P_{Wprox}. Thus, under the most challenging condition, PWdist gave rise to less pronounced deviations from a sinusoidal pattern (values of NPA closer to 1) than P_{Wprox} (see Fig. 2).

The above analysis of the effects of task difficulty and probe type on NPA provides grounding for the visual inspection of the (between-participant averaged) phase (Fig. 3) and Hooke (Fig. 4) portraits obtained under each condition. Variations in task difficulty (that is, variations in ID) gave rise to the same phenomena described for end-effector movement in earlier studies. For the lowest level of task difficulty phase portraits were close to circular and Hooke portraits close to linear, indicating that probe movement was quasi-sinusoidal. Within each half cycle the acceleration and deceleration phases were symmetrical, while the deceleration phase of half-cycle n (bringing the probe to stop within the target area) was fully merged with the re-acceleration phase of half-cycle n + 1 (driving the probe towards the other target). As ID increased, movement patterns lost their symmetrical character, due to the disproportionate increase in the duration of the deceleration phase with respect to the acceleration phase, as can be seen in phase space (Fig. 3) from the displacement of the peak velocities from the midpoint between the targets. At the same time, the deceleration of half-cycle n and the subsequent reacceleration of half-cycle n + 1 began to separate, as evidenced by the displacement of the point of peak acceleration from the point of movement reversal (Fig. 4).

Of particular interest for the present purposes was the influence of probe type on the movement patterns that appeared at the higher levels of task difficulty. In particular, the progressive deviations of trajectories from a perfect circle in phase space (Fig. 3) and from a straight line in Hook space (Fig. 4) were less pronounced for P_{Wdist} than for P_{Wprox}. At the lowest level of task difficulty movement was quasi-sinusoidal for both probes, but at the highest level of task difficulty P_{Wprox} gave rise to stronger non-linearities (a larger degree of asymmetry between acceleration and deceleration phases and a larger separation between deceleration and subsequent re-acceleration) than P_{Wdist}. These observations correspond to the finding that NPA was statistically different between probes only at the highest level of difficulty ($ID_{6.1}$).

4. Discussion

The present experiment examined the effect of end-effector mass distribution on task performance and underlying movement organization in the framework of reciprocal precision aiming. We hypothesized that tools with mass concentrated close to point of grasp would optimize performance of aiming tasks by allowing adjustments in the underlying perceptual-motor organization that minimize performance decrements as precision demands increase. To test this hypothesis, we crossed three levels of task difficulty with two types of probe varying in their maneuverability: one with mass concentrated close to the point of grasp (arguably more appropriate for fast precision aiming tasks) and one with mass concentrated far from the point of grasp (arguably less appropriate for such tasks). We evaluated the effect of task difficulty and probe type on (a) movement duration, a measure of task performance, and (b) the kinematic pattern of aiming movements, a window into the dynamics of underlying perceptual-motor organization supporting performance.

Movement duration was longer for smaller targets as predicted by Fitts' Law. Lengthening of movement duration as a function of task difficulty was mediated by changes in the kinematics of aiming patterns, as expected from the existing literature on precision aiming, whether the task is discrete (e.g., Beggs & Howarth, 1970; Elliott et al., 2001; MacKenzie et al., 1987) or reciprocal (e.g., Guiard, 1993; Huys et al., 2010; Mottet & Bootsma, 1999). For the lowest task ID, movement patterns were quasi-sinusoidal, as indicated by NPA values close to 1. Indeed, the shape of trajectories in Hook space suggests a linear dynamical organization supporting task performance. Put differently, the end-effector behaved as though governed by a linear stiffness function (Bongers et al., 2009; Guiard, 1993, 1997; Kelso, 1992; Mottet & Bootsma, 1999). The quasi-circular trajectories in phase space for the lowest ID suggest a mode of behavior with minimal interference with limb motion through non-linear dissipative mechanisms (Guiard, 1993, 1997). As tolerance for spatial variability at the end-point decreased (i.e. as target width was reduced), movement patterns became less sinusoidal, as indicated by the progressive deviation of NPA values from 1. The related changes in phase portraits index the increasingly prominent operation of non-linear dissipative processes (in particular Rayleigh damping[2]) in the underlying dynamic, which enhances end-effector stability to cope with the higher precision requirements. To allow time for the operation of dissipative processes, the movement system was constrained to slow down, particularly at the vicinity of the targets. Therefore, when faced with higher accuracy demands, the preferred strategy seems to be a local (rather than global) slowing down. Such strategy is revealed in the N-shaped form of the Hooke portrait at higher levels of difficulty. The implication is that at higher levels of difficulty the neuromuscular system behaved as though governed by a non-linear softening (Duffing[3]) stiffness function.

Probe type also affected both duration and kinematics of aiming movements, though effects were increasingly more pronounced as task ID increased. As expected, the proximally-loaded probe gave rise to significantly shorter MTs than the distally-loaded probe, an effect that increased in magnitude as the width of the target decreased. This result confirms that proximal loading yields a probe that optimizes performance of rapid aiming tasks. Regardless of probe type, the non-linear organizational process referred to earlier (notably Rayleigh damping and Duffing softening spring stiffness, cf. Mottet & Bootsma, 1999) came to the fore as task difficulty increased. However, at the highest level of task difficulty the contribution of non-linearities in these dissipative and conservative mechanisms was more pronounced (larger NPA) when participants used the proximally-loaded probe. This result is consistent with our hypothesis: proximal loading seems to allow adjustments in the dynamical organization of aiming patterns that minimize reduction in performance (here reduction in movement speed) as a function of increased task demands.

To reiterate, the particular Rayleigh-Duffing dynamical organization revealed here produces a local slowing down of the end-effector in the vicinity of the targets, which allows the stabilizing (dissipative) processes to reduce variability where it is needed. The higher stiffness around the center of oscillation produces faster movement (with less spatial control) when the end-effector is away from the target and spatial precision is not required. Therefore, Rayleigh-Duffing dynamics results in a reduction in spatial variability where it counts while minimizing movement time as much as possible (which is the task goal). Notably, the contribution of Rayleigh damping to the stability of aiming patterns is moderated by the inertial properties of the end-effector. For a given velocity, the distally-loaded probe will be less influenced by dissipative processes due to its higher inertia (or lesser maneuverability) than the proximally-loaded probe. The implication is that to achieve a similar level of end-point stability, participants would need to either increase the contribution of Rayleigh damping or scale down aiming speed. Results related to the kinematics of aiming patterns suggest the latter strategy was at play. The greater degree of global slowing down with the distally loaded probe is particularly visible in Hooke portraits (smaller deviations from a straight line) and confirmed by the lower magnitude of NPA. Perhaps increasing the contribution of Rayleigh damping would be too energy consuming or too inefficient when resistance to changes in rotational acceleration of the end-effector is high. In any case, the lesser maneuverability

[2] The operation of a Rayleigh function in an oscillatory regime yields an asymmetric velocity profile, with peak velocity occurring during the first half of a movement. Hence, the contribution of a Rayleigh type function to aiming dynamics is revealed by a skewing of the trajectories with peak velocities moving into the 2nd and 4th quadrants of the phase plane. Such deviations were especially prominent in the present experiment for higher ID's and P_{Wprox}.

[3] The operation of a Duffing function yields a non-linear relation between end-effector acceleration and position. When instantiating a softening-spring, stiffness is highest around the center of oscillation and progressively decreases outward. The contribution of this type of Duffing function to aiming dynamics is revealed by an N-shaped profile in Hooke's plane. Such deviations were especially prominent in the present experiment for higher ID's and P_{Wprox}.

of the distally-loaded probe seemingly prevented full exploitation of RayleighDuffing dynamic, which explains the longer movement times observed particularly at the highest level of difficulty.

The discussion above suggests that the proximally-loaded probe is more responsive to task sensitive adjustments in its pattern of motion. The flip side is that it must be controlled with less noise (or more precision). Bongers, Michaels, and Smitsman (2004) tested this assertion by observing the control strategy used when displacing an object with a longshafted rod varying in mass distribution. When the rod was loaded proximally, postures were selected to increase control of the rod (e.g. participants used a less extended arm synergy). Given this finding, it is possible that the greater nonlinearity associated with proximal probe loading might not simply reflect the preferred dynamical strategy for reaching small targets. It might also reflect the use of additional dissipative processes to comply with the greater stability requirements related to the probe's lower inertia. In that case, improvements in performance associated with proximal probe loading might be contingent on individual's capability to efficiently implement a more non-linear aiming dynamic that allows faster performance while maintaining the required level of accuracy. The greater inter-individual variability in kinematic patterns observed for the smallest target provides initial support to this possibility. The implication is that the benefit of proximal probe loading might disappear the presence of motor disabilities associated with noisier movement patterns (e.g. Parkinson's disease). In that case, distal loading might be more beneficial to task performance given its greater resistance to perturbation. This hypothesis can be tested in future experiments and if confirmed would contribute to theory development in tool use. In particular, it would suggest that the properties of a tool are insufficient to determine its potential to support performance of particular tasks; these properties would have to be considered with respect to the action capabilities of the tool user.

In contrast with the present study, Lin and Chen (2014) did not report significant differences in MT between conditions in which the probe was loaded proximally and distally to the handgrip. To explain this finding, the authors compared the load distribution of the probe with the gain setting in control-displays (Accot & Zhai, 2001; Jellinek & Card, 1990). When choosing the optimal gain setting, designers of control displays have to deal with a trade-off between gross-positioning time (acceleration time to get to the vicinity of a target) and fine-positioning time (deceleration time for final acquisition of the target). The authors assumed that with distal probe loading (analogous to a high gain setting), participants could quickly maneuver the instrument tip to the vicinity of the target but final acquisition time was longer due to difficulty in precisely controlling its position. With proximal probe loading (considered analogous to low gain setting) fine positioning was facilitated but there was a loss in terms of gross-positioning time. Accordingly, the authors argued that proximal and distal loading lead to different adjustments in movement pattern that are nonetheless related to similar increases in MTs.

Analysis of aiming pattern and dynamics in the present experiment does not support this interpretation: proximal loading yielded faster performance with higher degree of non-linearity when targets were smaller. This pattern of results suggests that proximal loading actually facilitates maneuvering towards the target (relatively lower gross-positioning time) but is actually more demanding in terms of fine-positioning (greater degree of non-linearity in damping and stiffness functions). Therefore, the lack of difference between proximal and distal loading reported by Lin and Chen (2014) might be related to the magnitude of the loading. While the added mass represented 10% of the total weight of the probe in their study, it represented 70% in the present study.

To our knowledge, this is the first study showing that biomechanical constraints at the level of end-effector can affect the higher order organization of aiming movements and not simply its execution. Pointedly, changes in the mass distribution of the probe generated more than a global change in movement duration; it affected the dynamics of precision aiming. Importantly, the effect of biomechanical constraints on the dynamics of precision aiming seems to be task dependent. Arguably, such effect might only show up when the particular biomechanical manipulation affects compliance with task requirements. For example, increases in the magnitude of transported mass (with no associated changes in mass distribution) require scaling of forces to produce the same end-effector trajectory during aiming tasks, but the manner in which torque should be directed is unchanged. As a result, manipulation of this particular biomechanical parameter generates a global slowing down of aiming movements without affecting its underlying dynamics (Fernandez & Bootsma, 2004). In contrast, changes in mass distribution of a hand-held tool modify the relative efficiency of strategies used to stabilize it when the task demands reaching at high speed. This might explain why adjustments in aiming pattern were only observed in the present study for the highest ID (smallest target). The effect of probe's mass distribution on performance and underlying dynamics of aiming movements for the lower IDs was not qualitatively different from the effect of transported mass observed by Fernandez and Bootsma (2004). The task specific effect of biomechanical constraints is consistent with minimal interference models of motor control (or models of motor abundance). These models would predict no changes in the perceptual-motor organization of movement patterns when variations in extant dynamical constraints do not affect task performance (Latash, Scholz, & Schöner, 2002; Todorov & Jordan, 2002).

There is evidence that adjustments in the kinematics of aiming patterns as a function of task level constraints (e.g. target size) are directed by ongoing visual information about geometric relations between target and end-effector in the context of task performance (Bootsma, Boulard, Fernandez, & Mottet, 2002; Fernandez & Bootsma, 2004; Fernandez & Bootsma, 2008; Fernandez, Warren, & Bootsma, 2006; Mottet et al., 2001). Arguably, the observed effects of probe type on movement patterns would be primarily driven by the haptic perceptual system, most particularly the haptic subsystem of dynamic touch. The demonstrated sensitivity of dynamic touch to mass-based properties of hand-held objects – lawfully related to the functions they can promote – provides support to this assertion (Hove et al., 2006; Wagman & Carello, 2001; Wagman & Carello, 2003; Wagman & Shockley, 2011). The role of dynamic touch would be to register the end-effector's mass moments in a form and manner that specify the patterning of muscular forces required for achieving the kinematic patterns appropriate for task performance. The mass distribution of the end-effector (here the probe) determines the possibilities for patterning forces by a particular individual. The possibilities for patterning forces in turn affect what patterns (or group of patterns) can be achieved. The haptic perceptual system might, therefore, co-direct adjustments in pattern to get the task done through detection of end-effector's mass distribution. Hence, the inertial properties of the probe seem to provide informational constraints for the organization of aiming patterns beyond those provided by task level demands. Therefore, perceptual-motor processes responding to task level constraints are likely sensitive to, and not independent from, processes organized in response to biomechanical, end-effector constraints as previously argued (Fernandez & Bootsma, 2004).

5. Conclusions

The performance of precision aiming tasks and the perceptual-motor organization of aiming movements are codetermined by the accuracy demands of the task and the inertial properties of the probe. Tools with mass concentrated close to the point of grasp allows achievement of the dynamical organization that produces an aiming strategy that produces the required level of stability while optimizing movement speed. Results suggest that task and biomechanical constraints influence precision aiming through interactive perceptual processes.

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References

Accot, J., & Zhai, S. (2001). Scale effects in steering law tasks. In *Paper presented at the proceedings of the SIGCHI conference on human factors in computing systems*. Seattle, Washington, USA.

Baird, K. M., Hoffmann, E. R., & Drury, C. G. (2002). The effects of probe length on Fitts' law. *Applied Ergonomics, 33*(1), 9–14.

Beek, P. J., & Beek, W. J. (1988). Tools for constructing dynamical models of rhythmic movement. *Human Movement Science, 7*(2–4), 301–342. Beggs, W. D. A., & Howarth, C. I. (1970). Movement control in man in a repetitive motor task. *Nature, 221*, 752–753.

Bongers, R. M., Fernandez, L., & Bootsma, R. J. (2009). Linear and logarithmic speed–accuracy trade-offs in reciprocal aiming result from task-specific parameterization of an invariant underlying dynamics. *Journal of Experimental Psychology: Human Perception and Performance, 35*(5), 1443–1457.

Bongers, R. M., Michaels, C., & Smitsman, A. W. (2004). Variations of tool and task characteristics reveal that tool-use postures are anticipated. *Journal of Motor Behavior, 36*(3), 305–315.

Bootsma, R. J., Boulard, M., Fernandez, L., & Mottet, D. (2002). Informational constraints in human precision aiming. *Neuroscience Letters, 333*(2), 141–145.

Bootsma, R. J., Fernandez, L., & Mottet, D. (2004). Behind Fitts' law: Kinematic patterns in goal-directed movements. *International Journal of Human-Computer Studies, 61*(6), 811–821.

Bootsma, R. J., & Mottet, D. (2004). Dynamic invariance in goal-directed aiming. *Ecological Psychology, 16*(1),

55–60.
Bootsma, R. J., Mottet, D., & Zaal, F. T. J. M. (1998). Trajectory formation and speed-accuracy trade-off in aiming movements. *Comptes Rendus de l' Academie des Sciences Serie iii-Sciences De La Vie, 321*(5), 377–383.
Buchanan, J. J., Park, J. H., & Shea, C. H. (2004). Systematic scaling of target width: dynamics, planning, and feedback. *Neuroscience Letters, 367*(3), 317–322.
Buchanan, J. J., Park, J. H., & Shea, C. H. (2006). Target width scaling in a repetitive aiming task: Switching between cyclical and discrete units of action. *Experimental Brain Research, 175*(4), 710–725.
Elliott, D., Helsen, W. F., & Chua, R. (2001). A century later: Woodworth's (1899) two-component model of goal-directed aiming. *Psychological Bulletin, 127*(3), 342–357.
Fernandez, L., & Bootsma, R. J. (2004). Effects of biomechanical and task constraints on the organization of movement in precision aiming. *Experimental Brain Research, 159*(4), 458–466.
Fernandez, L., & Bootsma, R. J. (2008). Non-linear gaining in precision aiming: Making Fitts' task a bit easier. *Acta Psychologica, 129*(2), 217–227.
Fernandez, L., Warren, W. H., & Bootsma, R. J. (2006). Kinematic adaptation to sudden changes in visual task constraints during reciprocal aiming. *Human Movement Science, 25*(6), 695–717.
Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology, 47*(6), 381.
Fitts, P. M., & Peterson, J. R. (1964). Information capacity of discrete motor responses. *Journal of Experimental Psychology, 67*(2), 103–112. Guiard, Y. (1993). On Fitts's and Hooke's laws: Simple harmonic movement in upper-limb cyclical aiming. *Acta Psychologica, 82*(1), 139–159.
Guiard, Y. (1997). Fitts' law in the discrete vs. cyclical paradigm. *Human Movement Science, 16*(1), 97–131.
Hoffmann, E. R. (1995). Effect of transported mass and constant force on times for ballistic and visually-controlled movements. *Ergonomics, 38*(5), 951–970.
Hoffmann, E. R., & Hui, M. C. (2010). Movement times of different arm components. *Ergonomics, 53*(8), 979–993.
Hove, P., Riley, M. A., & Shockley, K. (2006). Perceiving affordances of hockey sticks by dynamic touch. *Ecological Psychology, 18*(3), 163–189.
Huys, R., Fernandez, L., Bootsma, R. J., & Jirsa, V. K. (2010). Fitts' law is not continuous in reciprocal aiming. *Proceedings of the Royal Society of London B: Biological Sciences, 277*(1685), 1179–1184.
Jellinek, H. D., & Card, S. K. (1990). Powermice and user performance. In *Paper presented at the proceedings of the SIGCHI conference on human factors in computing systems*. Seattle, Washington, USA.
Kelso, J. A. S. (1992). Theoretical concepts and strategies for understanding perceptual-motor skill: From information capacity in closed systems to selforganization in open, non equilibrium systems. *Journal of Experimental Psychology: General, 121*(3), 260–261.
Konz, S., & Rode, V. (1972). The control effect of small weights on hand-arm movements in the horizontal plane. *AIIE Transactions, 4*(3), 228–233.
Langolf, G. D., Chaffin, D. B., & Foulke, J. A. (1976). An investigation of Fitts' law using a wide range of movement amplitudes. *Journal of Motor Behavior, 8*(2), 113–128.
Latash, M. L., Scholz, J. P., & Schöner, G. (2002). Motor control strategies revealed in the structure of motor variability. *Exercise and Sports Science Review, 30* (1), 26–31.
Lin, C. J., & Chen, H. J. (2014). Modeling movements of a long hand-held tool with effects of moments of inertia. *Human Movement Science, 34*, 233–245.
MacKenzie, C. L., Marteniuk, R. G., Dugas, C., Liske, D., & Eickmeier, B. (1987). Three-dimensional movement trajectories in Fitts' task: Implications for control. *The Quarterly Journal of Experimental Psychology, 39*(4), 629–647.
Mottet, D., & Bootsma, R. J. (1999). The dynamics of goal-directed rhythmical aiming. *Biological Cybernetics, 80*(4), 235–245.
Mottet, D., & Bootsma, R. J. (2001). The dynamics of rhythmical aiming in 2D task space: Relation between geometry and kinematics under examination. *Human Movement Science, 20*(3), 213–241.
Mottet, D., Guiard, Y., Ferrand, T., & Bootsma, R. J. (2001). Two-handed performance of a rhythmical fitts task by individuals and dyads. *Journal of Experimental Psychology: Human Perception and Performance, 27*(6), 1275–1286.
Plamondon, R., & Alimi, A. M. (1997). Speed/accuracy trade-offs in target-directed movements. *Behavioral and Brain Sciences, 20*(02), 279–303.
Saltzman, E., & Kelso, J. A. S. (1987). Skilled actions: A task-dynamic approach. *Psychological Review, 94*, 84–

106.
Todorov, E., & Jordan, M. I. (2002). Optimal feedback control as a theory of motor control. *Nature Neuroscience, 5*(11), 1226–1235.
Wagman, J. B., & Carello, C. (2001). Affordances and inertial constraints on tool use. *Ecological Psychology, 13*(3), 173–195.
Wagman, J. B., & Carello, C. (2003). Haptically creating affordances: The tool user interface. *Journal of Experimental Psychology: Applied, 9*(3), 175–186.
Wagman, J. B., & Shockley, K. (2011). Metamers for hammer-with-ability are not metamers for poke-with-ability. *Ecological Psychology, 23*(2), 76–92.
Woodworth, R. S. (1899). Accuracy of voluntary movement. *The Psychological Review: Monograph Supplements, 3*(3), 1–119.

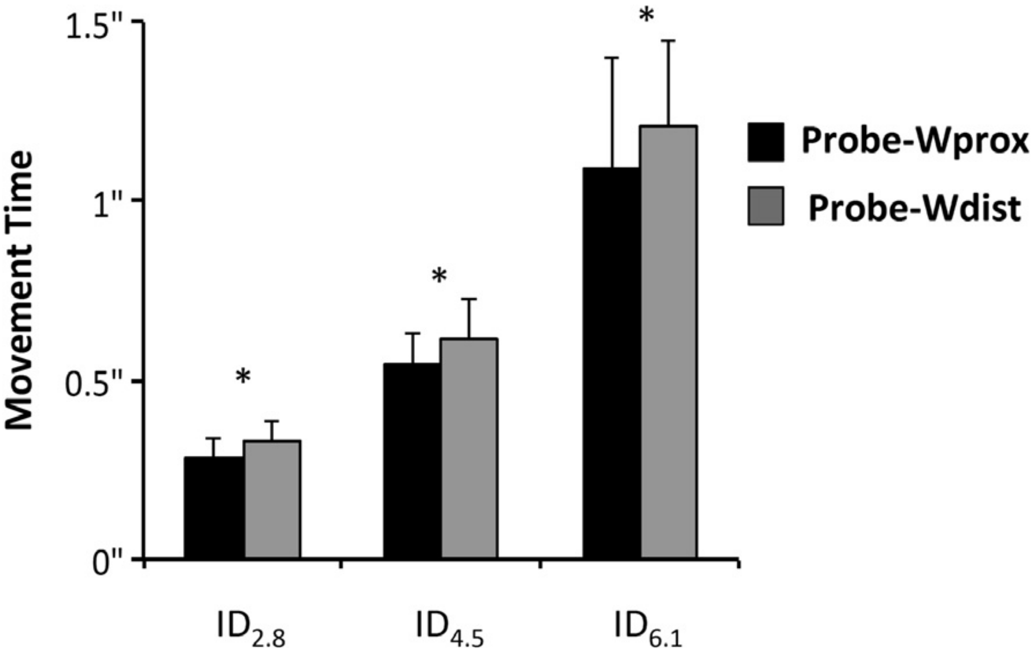

Fig. 1. Mean movement time (MT) as a function of task ID and probe type. (*) identifies significant differences between probe types

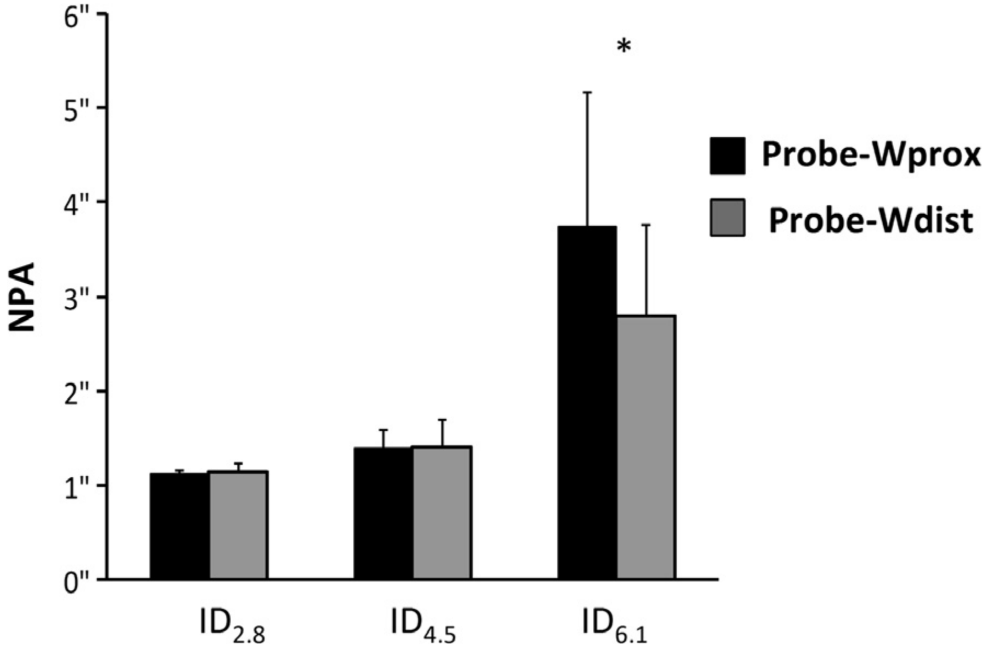

Fig. 2. Mean normalized peak acceleration (NPA) as a function of task ID and probe type. (*) identifies significant differences between probe types

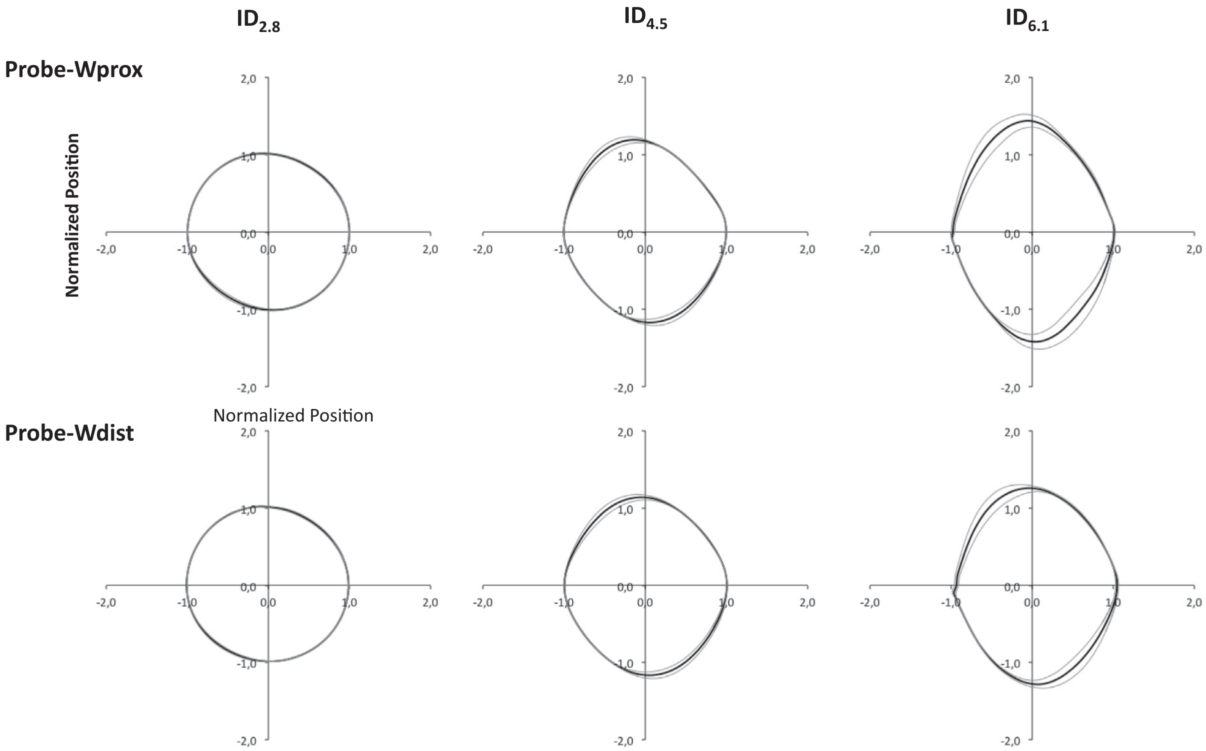

Fig. 3. Average phase portraits for each experimental condition. The area defined by gray curves indicates the 95% probability intervals around chance levels.

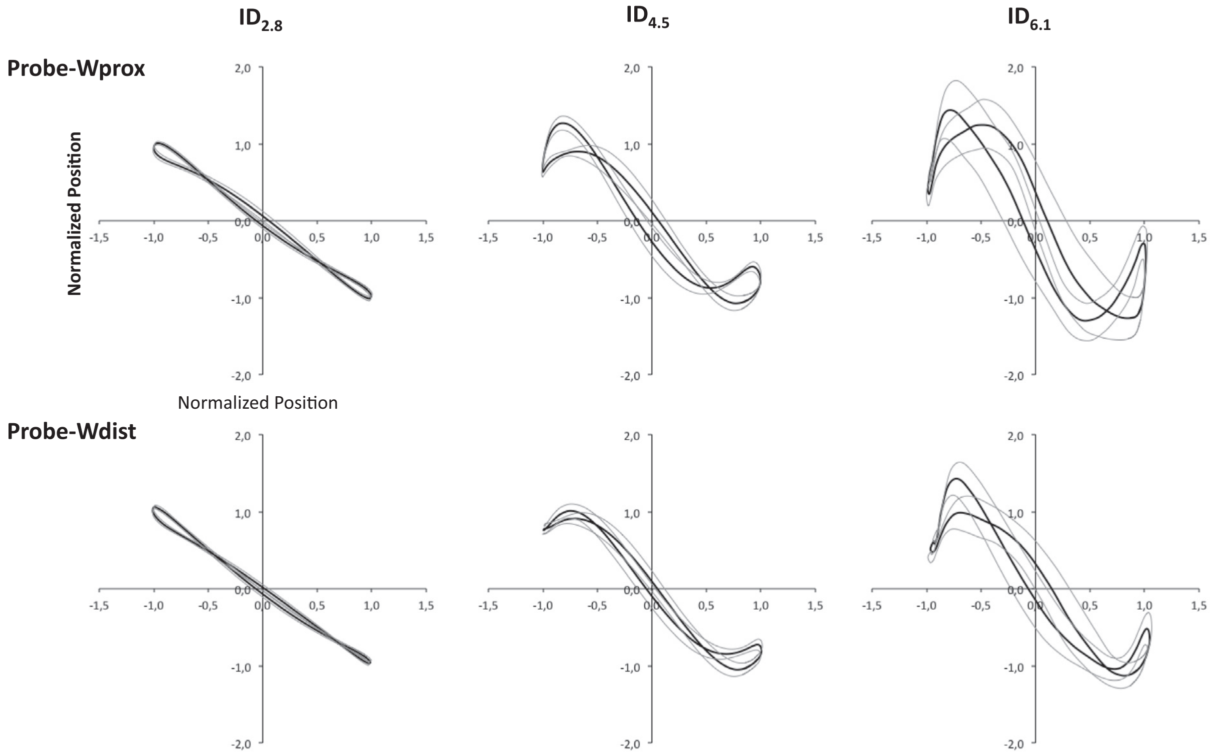

Fig. 4. Average Hooke portraits for each experimental condition. The area defined by gray curves indicates the 95% probability intervals around chance levels.