Passive wrist stiffness: The influence of handedness

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***Abstract*— Objective: This paper reports on the quantification of passive wrist joint stiffness and investigates the potential influence of handedness and gender on stiffness estimates.**

Methods: We evaluated the torque-angle relationship during passive wrist movements in 2 degrees of freedom (into flexion-extension and radial-ulnar deviation) in thirteen healthy subjects using a wrist robot. Experimental results determined intra-subject differences between dominant and non-dominant wrist and inter-subject differences between male and female participants.

Results: We found differences in the magnitude of passive stiffness of left and right-hand dominant males and right-hand dominant females suggesting that the dominant hand tends to be stiffer than the non-dominant hand. Left hand stiffness magnitude was found to be 37% higher than the right-hand stiffness magnitude in the left-handed male group and the right-hand stiffness magnitude was 11% and 40% higher in the right-handed male and female groups respectively. Other joint stiffness features such as the orientation and the anisotropy of wrist stiffness followed the expected pattern from previous studies.

Conclusion: The observed difference in wrist stiffness between the dominant and non-dominant limb is likely due to biomechanical adaptations to repetitive asymmetric activities (such as squash, tennis, basketball or activities of daily living such as writing, teeth brushing, etc.).

Significance: Understanding and quantifying handedness influence on stiffness may have critical implication for the optimization of surgical and rehabilitative interventions.

***Index Terms*— Asymmetry, Handedness, Laterality, Rehabilitation robotics, Wrist stiffness.**

I. Introduction

THE wrist is a delicate joint composed of eight carpal bones employed in most of our activities of daily living. Hand dominance is commonly associated with a preferential use of one hand to successfully perform tasks requiring sophisticated or forceful movements. Understanding the influence of this asymmetry on the wrist joint could elucidate how the neuromuscular system finely shapes our body to achieve superior dexterity. Furthermore, evaluation of limb preference and quantification of its impact on the musculoskeletal system could assist in Colles fracture surgical planning and in modifying rehabilitation programs to the patient specificities.

Indeed, passive joint stiffness has been suggested as a possible biomarker for estimating the efficacy of orthopedic surgical and rehabilitation interventions of the upper and lower extremities [1] [2]; [3]. Characterization of joint stiffness also expands our understanding of human biomechanics, such as human posture and the role of musculature in stabilizing posture [4]. However, an objective measure of joint stiffness is not readily available and clinical tests such as the Modified Ashworth Scale (MAS) are subject to high inter-rater variability, poor reliability [5] and validity [6].

From a clinical perspective, joint stiffness is often referred to as the resistance of a limb to passive motion [7]. From a mechanical perspective, stiffness is defined as the ability to store energy [8] or the steady state zero order (zero frequency) component of the mechanical impedance, which is defined by the dynamic operator that maps the time-history of displacement onto the time-history of force [7]. However, evaluation of stiffness is a tricky business because the raw experimental torque-angle relationship represents a complex combination of stiffness (k), inertia (m) and viscosity (b). As discussed by Latash and Zatsiorsky, the derivative dF/dx commonly used for describing stiffness depends not only upon k, m and b changes but also upon movement kinematics reflecting both the mechanical system and the perturbation.

Three terms are proposed in the literature [8]; [9] to define the derivative dF/dx according to the mechanical system and the method of testing: (a) Stiffness: The measurements are performed at equilibria. Resistance to the external force is provided by elastic forces, and potential energy is being stored. (b) Apparent stiffness: The measurements are performed at equilibria. The physical nature of the resistive forces is being disregarded. (c) Quasi-stiffness: The measurements are not performed at equilibria.

Quasi-stiffness is generally preferred to stiffness as it refers to the mechanical system's ability to resist externally imposed displacements disregarding the time course of the displacement and is not necessarily related to the ability to store elastic energy [8].

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In the present paper, passive joint stiffness and quasi-stiffness are used interchangeably. Passive joint stiffness is determined when all muscles crossing the joint are relaxed. Previous work has demonstrated that at a low velocity (to inhibit reflex feedback), quasi-stiffness and passive joint stiffness are essentially equivalent [8]; [9].

Previous studies have examined passive joint stiffness during wrist flexion-extension or wrist radial-ulnar deviation [10] [11] [12] [13]; [14], with more recent studies evaluating both planes of motion simultaneously in-vivo [2]; [3]; [15] and in-vitro [16]. However, the range of reported stiffness values varies widely in the literature, likely due to the different experimental methodologies.

Measuring joint stiffness involves two basic steps: measuring the torque response to a perturbation in displacement (or the displacement response to a perturbation in torque) and extracting stiffness from the measured torque-displacement. Previous studies employed different methods of applying the perturbation, e.g. impulse vs. step vs. ramp perturbations, or of determining joint stiffness using different data reduction methods (multiple regression, fitting ellipse, and thin plate spline method). Since there are differences in the reported results, we included a discussion of the influence of the data reduction method on stiffness estimates. Our analysis was performed using 3 data reduction methods (multiple regression, fitting ellipse, and thin plate spline method) to determine the variability of 3 stiffness ellipse parameters; size, shape and orientation.

Although previous stiffness studies [2]; [3]; [15] reported gender differences, no previous study compared systematically wrist stiffness in the dominant versus non-dominant arm. Hence this is the focus of our study. Stiffness ellipse features seem to be related to muscle characteristics: ellipse size to muscle cross-sectional area, ellipse shape and orientation to muscle configuration at the joint. Therefore, it is expected that repetitive asymmetric activities (asymmetric sports such as squash, tennis, basketball or activities of daily living such as writing, teeth brushing, etc.) that shape muscle growth and mechanical properties [27]; [28] might also have an impact on passive wrist stiffness. Quantification of handedness influence on stiffness could help to understand motor control strategies and muscle adaptations to a preferential use of one limb over another. Understanding biomechanical adaptations due to laterality has a wide range of clinical applications ranging from surgical planning to rehabilitation.

II. METHODS

A. Subjects

Thirteen healthy volunteers with no prior wrist surgery participated in this study (7 right-handed males – age range 19-55, mean 28.6; 3 right-handed females – age range 23-45, mean 30.3; 3 left-handed males – age range 23-60, mean 38). In our study, the hand used for handwriting was considered as the dominant hand. The Massachusetts Institute of Technology (MIT) Committee on the Use of Humans as Experimental Subjects (COUHES) approved the study; with all volunteers providing written informed consent prior to participation. Volunteers did not exercise 24 hours prior to the experiment. It has been shown that wrist eccentric exercise has an impact on the wrist ROM, perhaps due to muscle swelling [12] and short-range stiffness due to muscle thixotropic behavior [14][17][18][19] [20][21].

B. Robotic tool

Passive wrist stiffness was evaluated using a 3 degrees of freedom (DOF) wrist robot (Figure 1, InMotion 3.0 – Bionik Laboratories, Watertown, MA, USA) developed at the MIT Newman Lab [22]. The forearm neutral position was similar to the neutral forearm configuration reported in the literature [15] [3] and was in accordance with the ISB standard [15]; [23]. The robot design positioned the forearm so that the wrist joint was aligned with the rotation axes of the robot.

The wrist robot generates torques and simultaneously records the angular displacement produced into wrist flexion-extension (FE) and radial-ulnar deviation (RUD) [22]. Straps were used to lock the robot's and subject's forearm pronation–supination (PS) to reduce confounding movements during the trial. A gravity compensator was also included in the robotic controller to minimize the influence of gravity. The gravity compensator applied a constant force equivalent to the sum of an average hand mass plus the robot's handle mass. Although, the gravity effect depends on the wrist configuration we considered those fluctuations negligible for the range of motion considered in our study. A more precise measure of gravity compensation could have been achieved by measuring the hand mass of each subject and implementing a variable gravity compensator. Nonetheless, using an average hand mass allowed a more convenient set-up whilst reducing the influence of gravity as much as possible.

C. Experimental protocol

The trial commenced with random selection of the right or left arm. The reference position for the upper limb under examination was as follows; the wrist was in 0° extension, similar to the FE wrist position used by Pando et al [15]. While previous studies chose an almost neutral RUD wrist position (0° along ulnar deviation), we deliberately chose ulnar deviation (UD) of 7° as this initial wrist position was more comfortable and allowed the volunteer to stay in a passive state. To perform the wrist alignment, the third metacarpal was approximately aligned with the forearm to achieve wrist 0° extension, then wrist 7° ulnar deviation was roughly achieved by asking the volunteer to relax her/his forearm and not to bear the manipulandum. The wrist initial position recorded by the Wrist Robot was systematically checked to guarantee proper positioning.

Fig. 1. Wrist neutral positioning at the beginning of the experiment

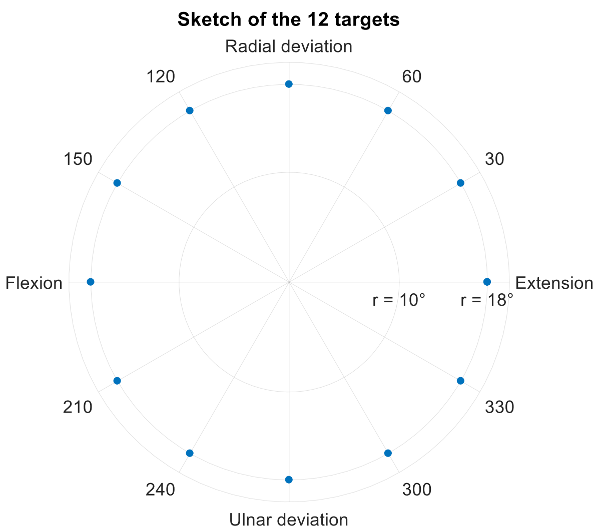

Fig. 2. Sketch of the 12 predefined targets for the subject's right arm in the FE – RUD space

As recommended by Pando et al [15], volunteers were encouraged not to actively grip the handle but to leave their fingers unconstrained and fully relaxed. This reference position was comparable to other wrist stiffness studies [2]; [15] allowing accurate analysis and comparison of study results.

We commanded the displacements, working with the limitation that the robot delivered up to 1.95 Nm. The robot recorded angular displacements and torques required to reach predefined targets (18 ° along each direction defined through the 2D FE-RUD space, see figure 2) at a predefined speed (between 0.1 and 0.2 rad/s to inhibit volunteer reflexes) [3]; [22]. If the resistance was too high to reach the target during a pre-defined time (2 seconds), the robot was programmed to return to the neutral position without completing the movement. Each trial consisted of 24 movements (inbound and outbound movements) along 12 equally-spaced directions through the space defined by FE-RUD. Each one of the 24 movements lasted approximately 2 seconds. At a slower speed, the experiment was less comfortable for the volunteers and we observed an increase in the occurrence of active muscle contraction. The 24 movements started from pure wrist extension for the right hand (pure flexion for the left hand) and proceeded counterclockwise with each of the 12 targets reached once. This cycle was repeated three times to reduce the influence of any artifacts (reflex or small muscle contraction). We collected data at 200 Hz with a resolution of 0.0006°. The robot motion was controlled with a proportional-derivative (PD) controller. The controller gains were set to 7 Nm/rad and 0.1 Nms/rad for the proportional and derivative gains respectively [2] [3] [15].

D. Analysis methods

To reduce the confounding influence of short range stiffness (2-4°) associated with inner-range joint movements [3]; [24] the torque-displacement data within 5 degrees of the neutral wrist position was removed, then the remaining data were centered (offsets in torques and angles were removed). The processed data was then applied to 3 different estimation methods commonly used in the literature to quantify 2 DOF passive wrist stiffness [2]; [3]; [15].

- the least square fitting ellipse method [3].

$$\begin{bmatrix} \boldsymbol{\tau_j}, || \\ \boldsymbol{\tau_j}, \perp \end{bmatrix} = \mathbf{Rj} * \begin{bmatrix} \boldsymbol{\tau_{FE}} \\ \boldsymbol{\tau_{RUD}} \end{bmatrix} \qquad \textbf{(1)}$$

$$\begin{bmatrix} \boldsymbol{\theta_j}, || \\ \boldsymbol{\theta_j}, \perp \end{bmatrix} = \boldsymbol{Rj} * \begin{bmatrix} \boldsymbol{\theta_{FE}} \\ \boldsymbol{\theta_{RUD}} \end{bmatrix} \qquad \textbf{(2)}$$

$$\mathbf{Kj} = \mathbf{regress}(\boldsymbol{\tau_j}, || \,, \boldsymbol{\theta_j}, ||) \qquad \textbf{(3)}$$

Where variable 'j' corresponds to one of the 12 directions considered through the FE-RUD plane, || means parallel to the wrist movement direction and ⊥ means perpendicular to this direction. MATLAB linear regression function was used to calculate the stiffness along each direction.

- the multiple regression method [3]; [7].

The joint stiffness matrix is calculated using the MATLAB linear regression function. The major and minor axes of the passive wrist stiffness ellipse match with the eigenvalues of the symmetric part of the passive wrist stiffness matrix [7].

$$[\boldsymbol{K_{FE/FE}} \quad \boldsymbol{K_{FE/RUD}}] = \boldsymbol{regress}(\boldsymbol{\tau_{FE}}, [\, \boldsymbol{\theta_{FE}}, \boldsymbol{\theta_{RUD}}]) \qquad \textbf{(4)}$$

$$[\boldsymbol{K_{RUD/FE}} \quad \boldsymbol{K_{RUD/RUD}}] = \boldsymbol{regress}(\boldsymbol{\tau_{RUD}}, [\, \boldsymbol{\theta_{FE}}, \boldsymbol{\theta_{RUD}}] \qquad \textbf{(5)}$$

- the thin plate spline method [25];[15].

The thin plate spline passing through the data is computed with a custom-made MATLAB function based on the MATLAB function tps. The spline f passing through the data minimizes a weight function with a smoothing coefficient p between 0 and 1 determining the bending of the plane, E is the error function, R the roughness, θ(j) and τ(j) are vectors along RE-RUD, x and y correspond to θ_{FE} and θ_{RUD}:

$$W(p,f) = p * E(f) + (1-p) * R(f) \quad \textbf{(6)}$$

$$E(f) = \sum_{j=1}^{n} (\tau(j) - f(\theta(j))) \quad \textbf{(7)}$$

$$R(f) = \iint \frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial x \partial y} + \frac{\partial^2 f}{\partial y^2} ds \quad \textbf{(8)}$$

3 paired t-test were performed for each subgroup using the ttest MATLAB function; right-handed males, right-handed females and left-handed males, to determine if the dominant hand exhibits a statistically significant higher stiffness magnitude when compared to the non-dominant hand. Another paired t-test was carried out comparing the dominant and non-dominant hand stiffness magnitude for all volunteers. The same statistical tests were applied to the other ellipse parameters (orientation and shape).

E. Method comparison

In order to analyze the 3 different methods of estimation, we compared the 4 parameters commonly used in the literature (listed below) to characterize a stiffness ellipse [3]; [7]. In addition, a fourth parameter (equilibrium position) was analyzed to fully characterize stiffness with a non-zero neutral starting position:

- The size: Stiffness magnitude (ellipse surface *(Nm/ rad)*^{2}*)*
- The orientation: Stiffness orientation (angle in degrees between RD direction and ellipse major axis direction toward RD, counterclockwise angles are considered positive)
- The shape: the ratio of the major axis of the stiffness ellipse to the smaller one
- The equilibrium position: the offset of the ellipse center corresponding to the FE and RUD offset angles

Furthermore, a Monte-Carlo method calculation was performed to identify the sensitivity to noise of each data reduction method. A white noise (using the MATLAB rand function) of amplitude 0.1 degree was added to FE and RUD displacements, and a white noise of amplitude max (torque) / 1000 was added to the torques in FE and RUD. The Monte-Carlo method was applied to the data from the 7 right-handed males (right and left-hands). The mean of the standard deviation of 100 iterations on each one of the 14 hands was used to compare the 3 different methods. The amount of noise applied to the displacement and torque data as well as the number of iterations was chosen to reduce the computation time of the thin plate spline method.

F. The Goodness of fit

To assess the goodness of fit of each reduction method, the coefficient of determination has been computed and averaged over all subjects and over all directions.

III. RESULTS

A. Noise sensitivity analysis

Results from the Monte-Carlo method are given in table 1. The multiple regression method is the least sensitive to noise with the lowest standard deviation for the three parameters; orientation (0.103±0.027°), shape (0.007±0.002) and size [0.016±0.004 (Nm/ rad)^2]. Hence, we employed the multiple regression estimation method as the model of choice to compare the left and right wrist stiffness values and to compare our results with existing literature. Nevertheless, although the MR method appears slightly superior to the other reduction methods in terms of noise sensitivity, FEM and TPS variability values from the sensitivity analysis are also lower than inter-subject variability so the three reduction methods can be considered robust enough to perform stiffness estimations.

TABLE. I

7 right handed males	MR	FEM	TPS
Stiffness Size (Nm/rad) ^2	0.016±0.004	0.027±0.011	0.042±0.011
Stiffness Shape	0.007±0.002	0.009±0.003	0.013±0.004
Stiffness Orientation (°)	0.103±0.027	0.166±0.046	0.348±0.122

Comparison of the sensitivity to noise of each reduction method (mean±SD). MR (multiple regression method, FEM (fitting ellipse method) and TPS (thin plate spline method).

B. Reduction method influence on stiffness estimations

Tables II to IV highlight the consistency of the stiffness values estimated by the three reduction methods along the 4 anatomical axes as well as the 3 ellipse parameters (size, shape and orientation). Ellipse parameters and stiffness values were reported along the four axes (0°, 90°, 180° and 270°) to afford direct comparison with 1-DoF studies. Graphical display is shown in figure 3. There is a small difference between the ellipse offset given by the fitting ellipse and the thin plate spline method likely caused by small differences in the stiffness values (cf stiffness values reported for the 4 anatomical axes). Stiffness values for males tend to verify the relation Krd>Kud>Kext≈Kflex, where Krd is the stiffness along wrist radial-deviation, Kud is the wrist ulnar deviation, Kext is the wrist extension, and Kflex is the wrist flexion, for both hands. For the 3 right handed females, the relation was shown to be Krd≈Kud>Kext≈Kflex. In addition, orientation values are highly symmetrical for both hands.

C. Main quantitative results

Stiffness ellipse size may be associated with muscle cross-sectional area and it was found higher in the dominant hand (Table V), with stiffness magnitude 11% higher in the dominant hand in the right-handed male population, 40% higher in the right-handed handed female population and 37% higher in the left-handed male population. This higher passive wrist stiffness in the dominant limb was found to show a significant difference for both right-handed female and left-handed male populations (right handed female dominant limb vs non-dominant limb and left handed male dominant limb vs non-dominant limb) but not for the right-handed male population (right handed male dominant limb vs non-dominant limb).

Geometric features such as the ellipse shape and tilt are generally associated with the joint geometry, muscle configuration and muscle passive forces. Those stiffness parameters were found roughly equivalent between both hands consistent with the fact that two arms are strongly symmetric with respect to the sagittal plane.

D. The Goodness of fit

Mean R^2 and standard deviation values have been reported in Table VI. Although coefficients of determination reported in our study are slightly lower than values reported in previous studies [3]; [15], our values are high enough to consider that a linear fit is a good approximation to estimate passive wrist stiffness.

IV. Discussion

Given the importance of the wrist in activities of daily living, an accurate description of wrist stiffness is of high value to understand our interactions with the environment and how the neuromuscular system must deal with multiple factors to achieve specific tasks. Handedness plays a major role in the way we interact with the world. Our ability to successfully perform specific tasks such as writing or playing squash strongly depends on the hand employed to perform the task. This preferential use of one limb over another implies sophisticated neural and/or biomechanical strategies to interact with the environment. We will compartmentalize the discussion as follows: first, we will compare our stiffness estimates with prior studies and discuss the potential reasons for the differences (experimental protocol, data reduction method, etc.). Then, we will discuss hand dominance and gender differences from a biomechanical perspective based on muscle fiber adaptations to exercises and theories about motor control adaptations to handedness. Finally, clinical implications will be discussed.

A. Comparison to previous studies

As highlighted by previous studies, stiffness depends on the range of motion (ROM) and its initial position [15]. Generally the following symmetric relation exists between wrist ROM and stiffness; $Krd>Kud>Kext\approx Kflex$ and $ROMrd<ROMud<ROMext\approx ROMflex$, where $ROMrd$ is the wrist range of motion along wrist radial-deviation [15].

Previous studies [2]; [3]; [15] employed different experimental protocols (neutral position, range of motion). Figure 4 summarizes the main differences.

Formica et al [3] considered a wrist neutral position, 10° in extension and an isotropic range of measurement of 17° along each direction approaching the wrist to its limit along extension and increasing the range of motion along flexion, which means $ROMrd<ROMud<ROMext<ROMflex$ rather than $ROMrd<ROMud<ROMext\approx ROMflex$. Formica et al [3] reported $Krd>Kud>Kext>Kflex$.

On the other hand, Pando et al [15] considered a wrist neutral position 0° along wrist extension and 0° along wrist radial deviation and an anisotropic range of measurement close to the wrist limits, which means $ROMrd<ROMud<ROMext\approx ROMflex$ and the study reported $Krd>Kud>Kext\approx Kflex$.

Drake et al [3] considered a wrist neutral position like Pando et al and an isotropic range of measurement of 15° in accordance with Formica et al with stiffness results closer to Pando et al.

In the present study, we considered a wrist neutral position, 0° along radial deviation and approximately 7° along UD with an isotropic range of measurement of 18°. This slight UD was deliberately chosen to position the subjects in a more comfortable position reducing the occurrence of involuntary muscle contractions and to increase the ROM along radial deviation (wrist RD range of motion is lower than wrist UD range of motion). The present protocol was designed to get the following relationship $ROMrd\approx ROMud<ROMext\approx ROMflex$ and the present study reports $Krd\approx Kud>Kext\approx Kflex$.

In addition, we analyzed gender differences on right hand wrist stiffness. The stiffness anisotropy corresponded to the ratio of the major to minor eigenvectors, which in our study was 2.48, consistent with the literature (2.94 [2] 1.58 [3]; and 2.69 [15]). The mean tilt of the ellipse for the right hand was 13.9 ± 7.1° using the multiple regression method, which was comparable to the values reported by [15] (12.1 ± 4.6°), lower than [3] (21.2 ± 9.2°), but higher than [2] (2.2±4.1°).

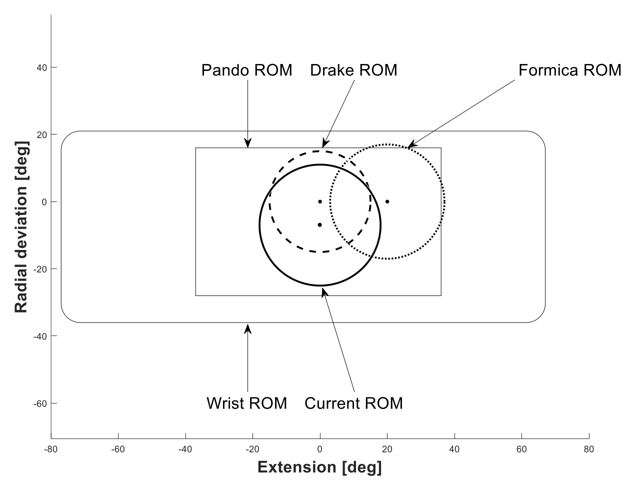

Fig. 4. Graphical representation of the previous and current protocols.

Analysis of stiffness magnitude values among different groups is consistent with the literature; right-handed females tend to have lower wrist stiffness values than right-handed males [2]; [3]; [15]. However, the stiffness orientation for the 3 right-handed females tended to be lower than the values previously reported [3]; [15]. The lower tilt recorded for the 3 right-handed females is likely due to a different wrist neutral position (slight ulnar deviation) and a different measurement range (18° along each direction around the pre-defined wrist initial position) [3]; [15]. Nevertheless, considering the sample size and the inter-subject variability, the present study stiffness estimations are consistent with past studies.

Stiffness magnitude estimates obtained using the fitting ellipse method were higher than values obtained with the multiple regression method and were consistent with the findings of Formica et al, 2012 [8.16 ± 3.7 (N.m/rad2) with the fitting ellipse method and 7.19 ± 3.4 N.m/rad2 with the multiple regression method]. The fitting ellipse method higher stiffness magnitude may be due to the higher sensitivity and impact of a single stiffness value along a direction on the overall stiffness magnitude. Although we employed a least square fit, a higher stiffness value along one direction will tend to stretch and increase the size of the ellipse. From the comparison of the three estimation methods, we adopted the multiple regression method. Based on the a-priori knowledge that a 2 DOF wrist stiffness has an ellipse shape [2]; [3]; [15], the multiple regression method is easy to implement, rapid, and less sensitive to noise as shown in Table I.

The combined effects of the experimental set up, the impact of the robotic design on the wrist placement, and the different reduction methods likely explain the variation in values reported in the literature. Further investigation on how the human-robot interface impacts the wrist stiffness estimate and the influence of neglected physiological phenomenon (such as muscle thixotropy) would be of great interest and perhaps allow more robust and repeatable stiffness measurements.

B. Hand dominance and gender influence on passive wrist stiffness

The present study suggests that the dominant hand tends to be stiffer than the non-dominant hand, which may support the argument that physical exercise has an impact on muscle properties [26]. Moreover, since all related studies [2]; [3]; [15] suggested that stiffness increases with muscle cross-sectional area, the present study confirms our expectations by showing that the dominant wrist tends to be stiffer.

Passive joint stiffness is related to muscle passive tension, which is associated with the myofibril structure. Repetitive asymmetric activities (such as handwriting, teeth brushing, etc.) could lead to a change in muscle fiber type, which could explain why passive stiffness of the dominant hand is higher. This hypothesis is supported by several studies reporting a higher percentage of slow-twitch muscle fibers in the dominant arm. It has been suggested that this biomechanical adaptation allows more sophisticated tasks to be performed and postures to be sustained for prolonged periods of time [27]; [28]. In addition, a study comparing rat soleus muscle (slow skeletal fibers) with rectus femoris muscle (fast skeletal fibers) reported that slow skeletal muscles have a higher tensile strength and tangent modulus than fast skeletal muscles [29]. The high stiffness and low strain of a slow tonic muscle would be appropriate for the function of a muscle adapted to sustaining stabilizing postures [29]; [4]. For example, handwriting can be cogently described as a daily asymmetric task, involving low level but sustained muscle activity around the wrist to stabilize the wrist and hand during writing. Based on this assumption, the activity performed by the dominant hand may lead to biomechanical adaptation of muscle fibers and an increase in passive wrist stiffness, to allow greater stability for high level, sophisticated movement tasks.

At first glance, the claim that properties of the dominant wrist adapt to achieve an accurate steady-state position seems to contradict research on brain lateralization. Sainburg (2014) suggests that the dominant arm is preferentially specialized for trajectory control, whereas the non-dominant arm is specialized for posture and accurate steady-state positions [30]. Nevertheless, specialization for trajectory control of the proximal arm does not a-priori imply the same role for the dominant hand. Furthermore, combining specialization of the dominant arm for trajectory control with specialization for posture and accurate steady-state positions of the dominant wrist would be a consistent biomechanical strategy to achieve sophisticated tasks, which is the assumed role of a dominant limb.

Geometrical features such as anisotropy and orientation [31], help to explain specific wrist features such as the dart thrower motion reported in past studies [31]. Neural control of the wrist selectively activates the movement pattern of least resistance in daily activities (hair combing, can opening, and shoe tightening). [32]; [31]; [3]. As expected, the present study shows that dominant and non-dominant wrist stiffness geometrical features are almost equivalent. In particular, orientation for the non-dominant wrist exhibits a tilt between the anatomical and mechanical axes consistent with the ones reported in all previous studies [2]; [3]; [15], suggesting that also for the non-dominant wrist the direction of least stiffness is aligned with the dart-thrower's motion. In addition, non-dominant wrist ellipse shape is also strongly anisotropic suggesting that for the non-dominant wrist the neuromuscular system must plan and/or control for this anisotropy when making wrist rotations [3] to achieve sophisticated tasks.

Wrist stiffness geometrical features are mainly associated with the joint geometry and muscle configuration [3]. Since it has been shown that the brain finely tunes limb stiffness geometrical characteristics to achieve greater dexterity [32]; [31]; [3], it seems consistent to expect some differences in the geometrical features between both hands associated with a preferential use of the dominant hand to perform sophisticated tasks. Prior studies about directional asymmetry of forelimb morphology [33];[34];[35] have demonstrated that hand dominance influences wrist bone geometry and bone mechanical properties. For example, geometric parameters such as inter-articular length (mid-shaft), cortical area (at mid-shaft) and medullary area (at mid-shaft) are bigger for the second metacarpal in the dominant hand [34]. Furthermore, there is a predominance of plate-like shapes in the trabecular micro architecture of the second metacarpal head of the dominant hand, while there is a predominance of rod-like shaped bone architecture within the non-dominant hand [35]. Lazenby et al suggests that the formation of plate-like bone results from higher loads being exerted upon the dominant hand [35]. Such differences in bone geometry and properties could slightly modify wrist kinematics and explain differences in the stiffness ellipse orientation between the right and left wrist. Nevertheless, we did not observe any statistically significant differences of the wrist geometrical features between both hands. Since passive joint stiffness corresponds to the passive muscle resistance to lengthening, it is consistent that stiffness ellipse parameters are mostly sensitive to muscle characteristics rather than to fine geometrical bone variation.

The dominant wrist higher stiffness is consistent with higher muscle cross-sectional areas linked to a preferential use for power activities and the “10% rule” which states that the dominant hand is approximately 10% stronger than the non-dominant hand [36]. This higher stiffness could also be associated with a change in muscle fibre type to perform fine motor activities [27]; [28]. Wrist stiffness geometrical features (shape and orientation) are very similar between both hands [32][31][3] suggesting that for the non-dominant wrist, previous assumptions about how the neuromuscular system must plan and/or control motion apply.

C. Clinical application

Limb preference may explain differences in strength and, more importantly, differences in learning and acquisition of functional skills as well as cerebral organization and hemispheric specialization [37]. For example, the determination of hand dominance might influence the interpretation of certain evaluation procedures such as grip strength and reaching accuracy [33]. Therefore taking handedness into consideration might be good practice in optimizing rehabilitation therapies [38]. As shown in past studies [33]; [37], hand dominance can be defined in multiple ways: (a) the relative preference for one hand in the execution of various unimanual tasks, (b) the greater skillfulness of one hand in the performance of these tasks, or (c) the greater strength of one hand which is supported by our results, i.e., higher stiffness in the dominant wrist. Beside handedness, muscle tone characterization is often part of a neurological exam, since increased mechanical joint stiffness is a common symptom of neurological disorders [3].

Previous studies estimating passive ankle stiffness in patients diagnosed with stroke and MS have shown that stiffness anisotropy is strongly impacted [39];[40]. Changes to the orientation and magnitude of joint stiffness in these patients has been shown to affect functional mobility and activities of daily living [40];[41]. Robot-mediated wrist stiffness evaluations might offer an additional tool to assess both a patient’s impairments and the effectiveness of therapy interventions targeting joint range of motion and abnormal muscle tone following neurological disorders. In addition, wrist orthopedic surgery often leads to of reduced joint mobility and higher stiffness [42]. Passive wrist stiffness estimations might be used as a supplementary tool to quantify the biomechanical impact of different surgical techniques and/or implants.

V. Conclusion

To our knowledge, this is the first study that characterizes the difference in passive wrist stiffness between the dominant and the non-dominant upper limb. These results highlight a new feature of the wrist joint relative to handedness and have the potential to enhance our understanding of "the most complex and poorly understood joint in the body" [43].

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Conflict of interest

H. I. Krebs is a co-inventor in several MIT-held patents for robotic therapy. He was one of the founders of Interactive Motion Technologies and 4Motion Robotics.

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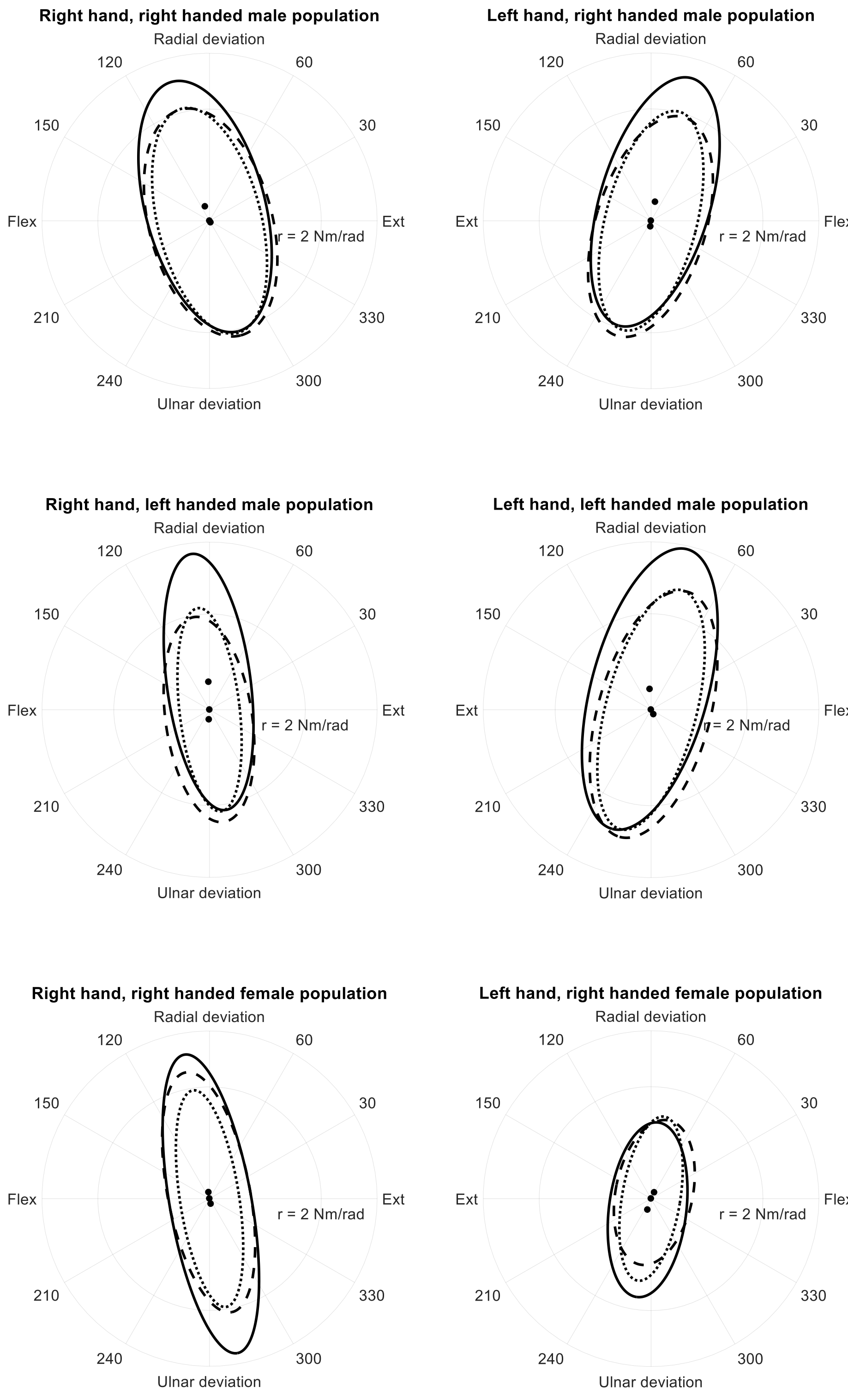

Fig. 3. Mean values for the dominant vs non-dominant hand for the three groups, FEM (solid line), MR (dots) and TPS (dashed line). Black dots correspond to the equilibrium points of the stiffness ellipses (only the symmetric part of the stiffness matrix).

Table II

7 right handed males	dominant hand			non-dominant hand		
Reduction methods	MR	FEM	TPS	MR	FEM	TPS
Stiffness (Nm/rad)						
Extension	0.89±0.18	0.88±0.32	1.07±0.23	0.79±0.13	0.94±0.18	0.97±0.14
Flexion	0.89±0.18	1.05±0.18	1.11±0.17	0.79±0.13	0.88±0.16	0.96±0.23
Radial deviation	2.08±0.42	2.09±0.55	1.94±0.44	2.03±0.42	2.18±0.49	1.87±0.43
Ulnar deviation	2.08±0.42	1.82±0.28	1.85±0.21	2.03±0.42	1.72±0.41	1.71±0.34
Ellipse parameters						
Shape	2.27±0.49	2.20±0.40	1.93±0.28	2.47±0.41	2.26±0.43	2.08±0.38
Size (Nm/rad)^2	6.11±1.94	8.19±2.83	7.47 ±1.99	5.27±1.64	7.62±2.71	6.65 ±2.48
Orientation (deg)	13.96±7.06	14.70±6.88	15.62±7.11	-14.42±4.45	-16.04±4.08	-15.85±5.19
Offset (rad)						
		-0.09±0.12	0.02±0.06		0.27±0.27	-0.03±0.14
		0.07±0.21	-0.01±0.12		0.31±0.45	-0.11±0.20

Comparison of the stiffness values and the stiffness ellipse parameters given by three reduction methods for both hands for the 7 right-handed males (mean±SD). MR (multiple regression method), FEM (fitting ellipse method) and TPS (thin plate spline method).

Table III

3 right handed females	Dominant hand			Non-dominant hand		
Reduction methods	MR	FEM	TPS	MR	FEM	TPS
Stiffness (Nm/rad)						
Extension	0.52±0.30	0.39±0.28	0.59±0.41	0.49±0.20	0.57±0.46	0.63±0.31
Flexion	0.52±0.30	0.67±0.34	0.61±0.28	0.49±0.20	0.63±0.28	0.72±0.28
Radial deviation	1.96±0.51	1.98±0.57	1.68±0.54	1.50±0.33	1.32±0.19	1.18±0.19
Ulnar deviation	1.96±0.51	1.97±0.68	1.77±0.68	1.50±0.33	1.50±0.14	1.27±0.17
Ellipse parameters						
Shape	4.44±2.15	3.96±1.12	3.50±1.57	3.12±0.85	2.77±0.81	2.22±0.40
Size (Nm/rad)^2	3.57±2.83	6.89±3.70	5.74 ±3.54	2.59±1.79	3.77±1.71	3.06±1.35
Orientation (deg)	8.74±3.74	14.70±6.88	15.62±7.11	12.15±13.58	13.01±11.05	15.84±12.68
Offset (rad)						
		0.04±0.13	-0.04±0.07		-0.24±0.61	0.25±0.40
		-0.04±0.10	0.04±0.06		-0.25±0.24	0.12±0.12

Comparison of the stiffness values and the stiffness ellipse parameters given by three reduction methods for both hands for the 3 right-handed females (mean±SD). MR (multiple regression method, FEM (fitting ellipse method) and TPS (thin plate spline method).

Table IV

3 left handed males	dominant hand			non dominant hand		
Reduction methods	MR	FEM	TPS	MR	FEM	TPS
Stiffness (Nm/rad)						
Extension	0.91±0.45	0.83±0.40	1.02±0.37	0.62±0.34	0.63±0.28	0.85±0.32
Flexion	0.91±0.45	1.26±0.67	1.23±0.40	0.62±0.34	0.59±0.34	0.74±0.33
Radial deviation	2.58±0.41	2.75±0.42	2.37±0.29	2.14±0.77	2.51±0.70	2.06±0.48
Ulnar deviation	2.58±0.41	2.34±0.55	2.21±0.48	2.14±0.77	1.70±0.68	1.71±0.59
Ellipse parameters						
Shape	3.00±0.91	2.55±0.73	2.45±0.63	3.94±2.07	3.32±1.06	2.49±0.62
Size (Nm/rad)^2	8.04±5.26	12.54±4.84	10.18±3.84	4.64±4.16	8.31±5.21	6.62±3.81
Orientation (deg)	-14.48±5.40	-15.82±10.51	-15.89±7.08	6.50±6.90	7.01±6.92	8.05±7.19
Offset (rad)						
		0.68±0.39	-0.22±0.14		-0.02±0.04	-0.02±0.03
		0.37±0.71	-0.11±0.19		0.03±0.54	0.04±0.18

Comparison of the stiffness values and the stiffness ellipse parameters given by three reduction methods for both hands for the 3 left-handed males (mean±SD). MR (multiple regression method, FEM (fitting ellipse method) and TPS (thin plate spline method).

Table V

	7 right handed males			3 right handed females			3 left handed males		
Methods	MR	FEM	TPS	MR	FEM	TPS	MR	FEM	TPS
Anisotropy %	-8,8	-2,7	-7,8	29,7	30,1	36,6	-31,3	-30,2	-1,6
Magnitude %	13,7	7,0	11,0	27,5	45,3	46,7	42,3	33,7	35,0
Tilt %	-3,3	-9,1	-1,5	-39,0	11,5	-1,4	55,1	55,7	49,3

Comparison dominant vs non-dominant ellipse parameters given by three reduction methods for both hands for the 3 populations (mean±SD). MR (multiple regression method, FEM (fitting ellipse method) and TPS (thin plate spline method). We report the differences between dominant and non-dominant in terms of:
(Dominant values – Non-dominant values / Dominant values) *100

Table VI

	Coefficient of Determination R^2		
Method / Movement Direction	Multiple regression method	Fitting ellipse method	Thin plate spline method
Inbound movements	0.865±0.075	0.917±0.038	0.958±0.038
Outbound movements	0.920±0.036	0.852±0.069	0.967±0.026

Comparison of the coefficient of determination (mean ± standard deviation) between each reduction method.