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Factors affecting the sensitivity to small interaction forces in humans*

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***Abstract*— Effective physical human-robot interaction (pHRI) depends on how humans can communicate their intentions for movement with others. While it is speculated that small interaction forces contain significant information to convey the specific movement intention of physical human-human interaction (pHHI), the underlying mechanism for humans to infer intention from such small forces is largely unknown. The hypothesis in this work is that the sensitivity to a small interaction force applied at the hand is affected by the movement of the arm that is affected by the arm stiffness. For this, a haptic robot was used to provide the endpoint interaction forces to the arm of seated human participants. They were asked to determine one of the four directions of the applied robot interaction force without visual feedback. Variations of levels of interaction force as well as arm muscle contraction were applied. The results imply that human's ability to identify and respond to the correct direction of small interaction forces was lower when the alignment of human arm movement with respect to the force direction was higher. In addition, the sensitivity to the direction of the small interaction force was high when the arm stiffness was low. It is also speculated that humans lower their arm stiffness to be more sensitive to smaller interaction forces. These results will help develop human-like pHRI systems for various applications.**

***Clinical Relevance*—This research helps improve pHRI by understanding how humans physically interact. This information could be used to develop safe and intuitive medical robots for elder and neurological patients, and benefit healthcare in the long term.**

I. Introduction

Conventional robots have been used in various application areas such as healthcare [1] and manufacturing [2, 3]. In most of these applications, robots perform only predefined tasks where they do not need to interact and follow human commands in a continuous fashion [4]. In contrast, interactive robots are expected to be used in physically closer applications to humans through direct arm contact. They are used to perform cooperative interaction tasks with humans [4], such as in robot-assisted surgery or exoskeleton robots [5]. Ongoing demand for quality nurses, therapists, and productivity in production increases the need for such human-like interactive robots. They have significant potential in nursing and patient care applications including rehabilitation, physical therapy, etc. Additionally, interactive robots may serve as full-time or temporary human caregivers for disabled elders and neurological patients [5, 6].

Despite the technological advancement of robotics, for interactive robots to support human movement during human-like interaction tasks, there remain technological gaps for safe, intuitive, and effective physical human-robot interaction (pHRI). To develop a human-like interactive robot, it is important to first know how humans physically interact with one another, to exchange their intentions and reactions through the physical coupling [4]. Indeed, humans are experts in physical interaction. Through non-verbal physical human-human interaction (pHHI), human dyads can improve their performance [7, 8], detect each other's roles [9], and distinguish motor experience [10] through interaction forces only (forces acting at the interacting or coupling points between hands of two humans).These information-rich interaction forces are approximately 20N or less in magnitude [10], and often even around 1N (small interaction forces) [11]. Therefore, the sensitivity of small changes of interaction forces is required for motor communication between human-human and human-robot dyads. Humans seem capable of decoding information from these small interaction forces.

Then, how do humans sense and interpret small interaction force during physically interactive tasks? While many prior research studied the human motor control of arms in seated human-robot experiments, they did not investigate the mechanism through which interaction forces are sensed by the user [6, 8, 9, 12-14]. A possibility is that humans detect small interaction forces through the mechanoreceptors at the skin of the hand [4, 7, 8]. However, these skin receptors may be ineffective to identify the subtle changes of the small interaction forces if the preload due to secure hand grip is much greater than the changes in the magnitudes of force [13, 15]. Alternately, proprioceptors in the joints and muscles, such as muscle spindles or Golgi Tendon Organs, may detect arm movements as a result of small interaction force. As long as the arm stiffness is maintained low, small changes in force may generate sufficient arm movement that is detected by the proprioceptors and interpreted by the human.

To this end, the aim of this paper is to find the factors that can affect the sensitivity to small interaction forces during pHRI. The hypothesis of this work is that a better sense of the small interaction force is obtained if the corresponding movement of the arm is aligned with the applied force. In addition, lower stiffness that is favorable for larger movement will improve the sensitivity to small forces.

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II. Materials and Methods

A. Experimental Setup

The hypothesis and experimental protocol of this research work are preregistered in the open science foundation (https://osf.io/qbmcx). 20 healthy young adults were recruited for this research (19 males and 1 female, 22.1±4.0 years of age). All participants were right-handed and had no prior neurological disorders or diseases. While the population was biased to right-handed individuals, we assumed that left-handed participants will not have different sensitivity to interaction forces. The experimental protocol and procedures were approved by the institutional review board (IRB) of the University of Missouri. All subjects gave their written, informed consent.

The experiment involved a haptic robot (Phantom Premium 1.5/6 DOF-HF, 3D Systems, USA) that provided interaction forces to the arm of a seated participant while they held the robot handle as shown in Fig. 1(a). Shoulder straps were used to maintain the back of the participants against the rigid chair throughout the experiment. All participants maintained a specific posture (distance between the sternum and right arm was ~30% of arm length, ~71° shoulder abduction angle, 45° shoulder horizontal flexion, 90° elbow flexion, and wrist, forearm in their neutral 0° position) during the experiment [14]. The level of forearm flexor muscle contraction was measured using single-channel electromyography (Spikershield #V2.61, Backyard brains, MI, USA) to ensure that participants had two different levels (high and low) of grip forces to hold the robot arm. The haptic robot applied two different levels of interaction force (low: 0 → 1N and high: 0 → 2N) for ~5-seconds to the arm that increased gradually as shown in Fig. 1(b). Between ~3 to ~5-seconds the levels of forces were kept constant at their maximum values (1N or 2N). The gradual increase of interaction force was intended to avoid stretch reflexes The robot provided the interaction forces in four different directions (+Z,-Z, +X,-X) as shown in Fig. 1(c).

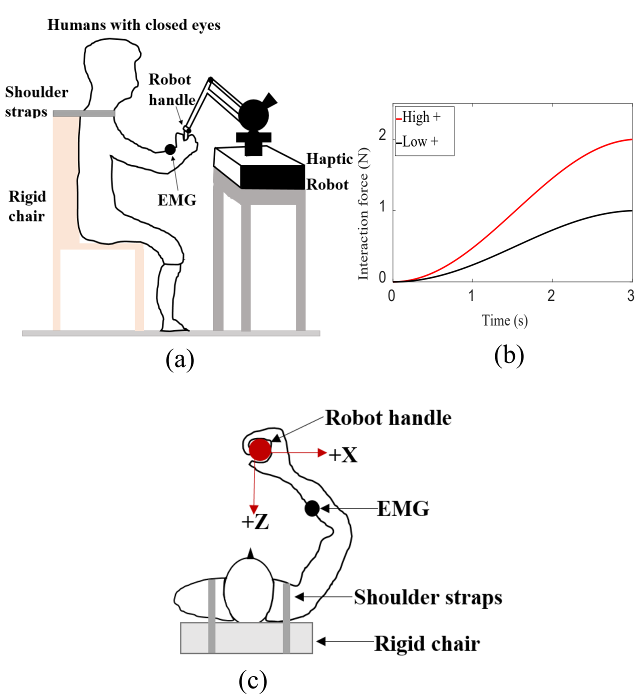

Figure 1. (a) Experimental setup (b) force profile for high (2 N) and low (1 N) robot interaction force up to 3 sec (c) top view of experimental setup

B. Experimental Protocol

All participants maintained the specific right arm posture with their eyes closed. Participants were asked to close their eyes to sense the direction of interaction forces only through their handholding otherwise they could see the movements of robot arms through visual feedback. Two different levels of interaction force (high: 2N, low: 1N) were applied to the participants' hands while they maintained one of two levels of forearm flexor muscle contraction (high: 70-80% MVC, low: 0-20% MVC) in such a way that there were high (70-80% MVC) or low grip forces (0-20% MVC), constituting four different experimental conditions (HH- high force high muscle contraction, HL- high force low muscle contraction, LH- low force high muscle contraction, and LL- low force low muscle contraction). Each participant performed a total of 96 trials that consisted of 24 trials of each of the four conditions (HH, HL, LH, and LL). For each condition, the force was applied 6 times in each of the four orthogonal directions (+*X*, -*X*, +*Z*, or -*Z*).

C. Data Processing and Analysis

In addition to the participant's responses, the setup also measured the alignment of arm movement with the directions (+X and +Z, Fig. 2(a)) of robot interaction force.

$$\theta = \tan^{-1}\left(\frac{|dz(t)|}{|dx(t)|}\right) \tag{1}$$

$$\theta = \tan^{-1}\left(\frac{|dx(t)|}{|dz(t)|}\right) \tag{2}$$

where, dz and dx are the displacements of the robot handle from the initial position (t=0) in the Z and X directions at the point where radial displacement for a trial (0-5 seconds) was maximum that can be calculated using dx and dz.

$$R = \max\left(\sqrt{dx(t)^2 + dz(t)^2}\right), t = [0, 5] \tag{3}$$

In this experiment, arm stiffness was also estimated from the interaction forces that is commanded to the robot and the arm (robot handle) displacements. The two-dimensional stiffness was calculated by the following equation [12].

$$\begin{bmatrix} F_x \\ F_z \end{bmatrix} = \begin{bmatrix} K_{xx} & K_{xz} \\ K_{zx} & K_{zz} \end{bmatrix} \begin{bmatrix} dx(t) \\ dz(t) \end{bmatrix} \tag{4}$$

where F_x and F_z are the robot commanded interaction forces in the X and Z-direction, K_{xx}, K_{xz}, K_{zx}, and K_{zz} are the elements of the 2-dimensional stiffness matrix. The stiffness elements and stiffness norm were calculated using a linear least square regression model. To overcome dynamic effects, stiffness was measured at 3 seconds for the high and low levels of forces. For comparing the stiffness at 1N, the stiffness was also measured at 1.5 seconds during the high-force trials.

For statistical analysis, a generalized linear mixed model was used to find the data in trial-by-trial manner, where correct and incorrect responses were the binomial outcomes where no-response was considered as an incorrect response. This analysis included the fixed effects of the alignment of arm movement to the force (angle). Two-way analysis of variance (ANOVA) was used to find the effect of low robot interaction force and high muscle contraction on the stiffness norm.

III. Results

A. The alignment of arm movements to interaction forces affects the sensitivity

Among 1443 correct trials and 477 incorrect trials where 255 trials were no-response for all participants, the sensitivity to small interaction forces was high when the misalignment of arm movement with the force direction was low (Fig. 2(b)). The highest sensitivity was observed when the arm movement was exactly along the direction of the applied robot interaction force. These trends were statistically significant ($p<0.05$). The linear mixed-effects model of the angles showed that the sensitivity to small interaction forces was decreased by the increase of misalignment of arm movement (negative estimate,-0.06442). The odds ratio (0.937) was found to be less than 1, which indicates that subjects were 0.937 times as likely to be correct for a 10° increase of the misalignment angle.

B. Higher arm stiffness decreases sensitivity to small interaction forces

The human arm stiffness norm for the high and low levels of interaction force was correlated with the sensitivity to the force direction (Fig. 3). Linear regression for the trials with a high level of interaction force (2N) showed a correlation of R^2=0.2470 between the percentage of correct responses and the stiffness norm where forearm muscle contraction varied between high (H: 70-80%MVC) and low (L: 0-20%MVC). Similarly, linear regression of small interaction force (1N) provided a correlation of R^2=0.50. However, the coefficients (slope) of linear regression for high interaction force was -0.03942, while it was -0.1606 for small robot interaction force, which indicates that the reduction of sensitivity with the increase of stiffness norm was more pronounced for smaller interaction forces.

C. Arm stiffness is low at lower interaction force

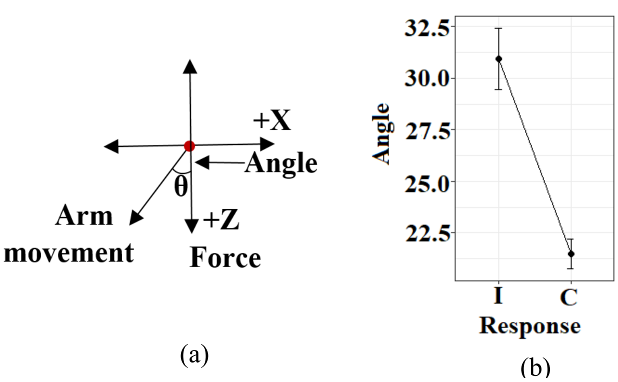

Figure 2. (a) Representation of arm alignment (angle) with the direction of interaction force (b) correct responses had a lower average angle with the direction of applied robot interaction force than incorrect responses (ANOVA analysis)

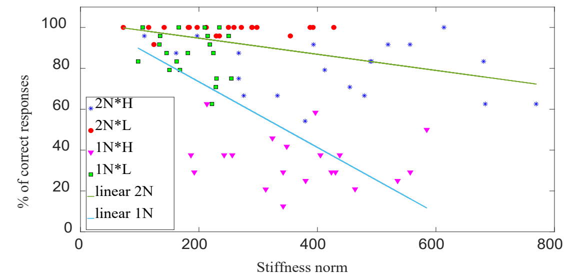

Figure 3. Percentage of correct responses increases with the decrease of stiffness norm of human arm during pHRI (slope and R^2 values for high force (2N) was -0.03942 and 0.2470, for low force (1N) they were -0.1606 and 0.50 respectively)

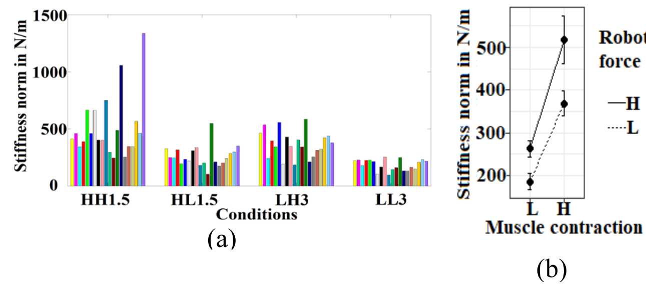

Figure 4. (a) Human arm stiffness is high for high interaction force (2N) and low for lower interaction force (1N) trial for the same level of muscle contraction (different color denotes different subjects) (b) ANOVA analysis of stiffness norm for high and low level of interaction force

TABLE I. OVERALL HUMAN ARM STIFFNESS DURING HIGHER (2N) AND LOWER LEVELS OF FORCE (1N)

Stiffness (N/m)	Condition 1 *Time 3 sec and force 2N*		Condition 2 *Time 1.5 sec and force 2N*		Condition 3 *Time 3 sec and force 1N*	
	HH	HL	HH	HL	LH	LL
K_{xx}	312.81	205.11	346.93	204.29	263.67	156.11
K_{xz}	-8.36	-17.13	7.17	-10.29	17.72	-8.02
K_{zx}	21.86	-20.67	3.95	-15.93	26.30	-10.93
K_{zz}	371.85	207.15	399.01	211.82	305.01	158.98

Table II. FIXED EFFECTS OF STIFFNESS NORM USING LINEAR MIXED MODEL

	Estimate	Std. Error	df	t value	Pr (>|t|)
Intercept	280.81	30.72	69.20	9.141	1.61e-13 ***
Robot low	-112.47	33.89	58.00	-3.32	0.00157 **

The estimated stiffness of human arm varied with the level of interaction force despite the instructions to the participants to maintain a constant level of muscle contraction (%MVC) (Fig. 4). The stiffness norm (2N) was calculated from the force-displacement relationship at t=3 seconds as well as t=1.5 seconds, while only at 3 seconds for the small interaction force (1N), since after 1.5 seconds in the high force trial, the magnitude of force was equal (1N) to the small interaction force trial (1N) at 3 seconds. All the stiffness values were averaged across all participants and trials for all four conditions. It was observed that all the subjects were stiffer in the Z direction than X-direction force as $K_{zz}>K_{xx}$ for all the four conditions (Table I, 399.01 N/m>346.93 N/m, 211.82 N/m>204.29 N/m, 305.01 N/m>263.67 N/m, and 158.98 N/m>156.11 N/m). Also, stiffness at 2N force at 3 and

1.5 seconds trials were comparable with each other (Table I, HL=205.11 N/m= ~204.29 N/m), while higher for 1N at 3 seconds trial (Table I, 312.81 N/m >263.67 N/m, 371.85 N/m >305.01 N/m, 207.15 N/m > 158.98 N/m). These trends were statistically significant ($p<0.001$, Fig. 4(b)). It was also observed that the stiffness norm was higher for high robot interaction force, while lower for a lower level of interaction force, regardless of the level of muscle contraction (Fig. 4(b)).

For the same 1 N of force, the average stiffness norm was higher (399.6 N/m) for HH at 1.5 sec than for LH at 3 seconds (314.57 N/m). Similarly, the average stiffness norm was higher (221.71 N/m) for HL at 1.5 sec, compared to the LL condition (167.13 N/m) at 3 sec. All these trends were statistically significant (Table II, $p<0.001$). Conditions with smaller interaction force decreased the stiffness norm by 112.47 N/m although participants maintained the same level of muscle contraction (Table II).

IV. Discussion

Humans may sense the direction of interaction force through the cutaneous pressure receptors of their palms during pHHI and pHRI. However, the results in this work suggest that higher alignment of arm movement to the direction of force increases the sensitivity of small interaction force, despite the fact that the force direction does not change and the pressure receptors could have detected the direction of force. This suggests that accurate arm movement direction, and not force direction, is important in detecting the direction of the push or pull with small forces. This further implies that the proprioceptors that detect the arm movement, such as the Golgi tendon organs or muscle spindles, may be more suitable for detecting small interaction forces than the pressure receptors at the hand. This is especially true when the grip force dominates the preloaded pressure on the cutaneous sensors [16], as can be seen by the reduced sensitivity during high muscle contraction trials in which the grip forces are higher.

For proprioceptors to detect the force, however, sufficient arm movement should be generated at the direction of the force. At higher arm stiffness, the displacement or movement of the arm may be insufficient and thus reduce the sensitivity to small interaction forces. The results in Fig 3. illustrates this interpretation that, in addition to reducing the efficacy of the cutaneous sensors by increasing the preload, high muscle contraction also leads to higher arm stiffness that will also reduce the efficacy of the proprioceptors.

A notable observation was that the arm stiffness was higher when the applied force was high (2N), even though the muscle contraction remained similar. A possible explanation is that higher force created faster and larger movements which results in larger stiffness due to stretch reflex as well as the non-linear force-to-length relationship of the muscles. Alternatively, humans may have reduced their arm stiffness, perhaps unconsciously, to better sense the direction of small interaction force (1N). The muscle contraction measure may not have captured this due to inherently noisy signals. Further investigation on this phenomenon may benefit from more accurate measurement of muscle activities as well as a direct measure of the interaction force.

V. Conclusion

This research work was motivated by the need to develop an effective human-like interactive robot. It is suggested that low arm stiffness with better alignment of arm movement with the direction of force may help improve physical communication through small interaction force during pHRI.

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