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The Influence of Discrimination Strategy on the JND in Human Haptic Perception of Manipulator Stiffness

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To better design and evaluate simulator control loading systems, humans' JND in the haptic perception of manipulator stiffness was investigated. To assess changes in such a mechanical property, humans must infer the change through changes in perceived contact force and/or manipulator displacement. To study the relative roles of these two perceptions, we measured stiffness JNDs of seven participants through a forced-choice stiffness discrimination procedure, on three conditions which we referred to as the force, displacement and free conditions. In the force condition, the manipulator displacement was fixed and subjects could only base their stiffness discrimination on changes in the contact force, and likewise in the displacement condition, discrimination was on the basis of changes in the manipulator displacement while the contact force was fixed. In the free condition subjects could uses either or both force and displacement cues to discriminate between different stiffness settings. The lowest stiffness JND was observed in the force condition, followed by a similar results from the free condition. The highest JND level and a poor consistency of results among individuals were obtained in the displacement condition. Subjects indicated that their stiffness discrimination in the free condition was based on the force comparison. To validate this finding, we used two models, one assumed force differences as a criterion for detection and the other assumed the displacement, to estimate the experimental results. Model comparisons indicated that subject's stiffness discrimination is largely based on detection of force differences.

I. Introduction

The Control Loading System (CLS) is of importance to a flight simulator, as it aims to provide pilots with the right "control feel" on the manipulator during simulation. The similarity between dynamics of the simulated manipulator and dynamics of the manipulator in a real aircraft is generally referred to as fidelity. In order to present the pilot with the proper feel, such that the pilot trainee obtains the right skills that they can correctly transfer to the real aircraft, the fidelity is a key factor for a simulator's feel system design.

The CLS generally simulates a manipulator by an admittance causality,[1] as shown in Fig. 1. With this control protocol, the CLS moves the inceptor (the manipulator) in response to the measured force. The desired inceptor motion is calculated in real-time in the control loading computer, according to the dynamic model of the desired manipulator.

Differences exist in the presented control dynamics, for instance due to time delays in the digital system, and magnitude changes and phase lags in the response of the servo system. As all sorts of thresholds are known to exist in humans' haptic perception, questions on whether humans are capable to feel the difference between real and simulated manipulator dynamics have yet to be answered, which could provide better guidelines to the CLS design. The linear dynamics of a manipulator are generally determined by mechanical properties such as the spring stiffness, damping and mass. Answering the above questions requires knowledge on humans' haptic just noticeable difference (JND) in perceiving these properties.

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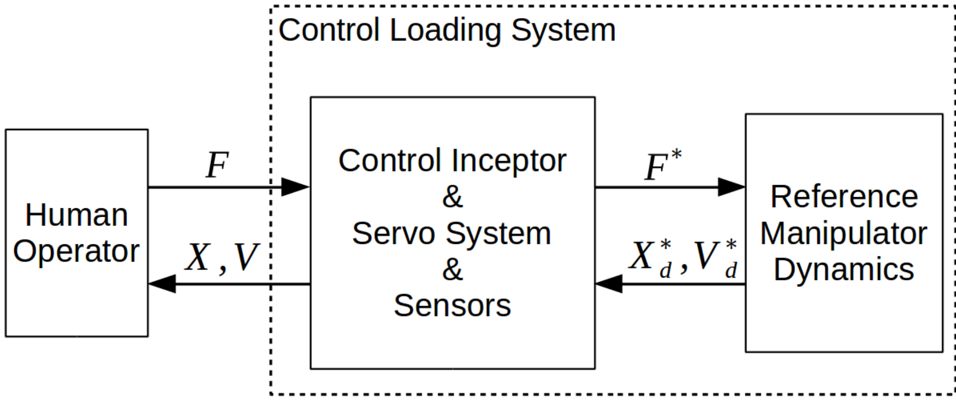


Figure 1: General structure of the control loading system with an admittance causality. Here, F denotes the force that a pilot applies on the control inceptor, X and V are the angular displacement and velocity of the inceptor. Superscript "*" denotes the discrete signals.

In the current work, we will investigate the JND in perceiving stiffness, as this property relates to a manipulator's static response and bandwidth, hence contributes an important part to the feel of control. Humans could only estimate the stiffness, since no known receptors in haptic system measure this quantity directly. During the interaction with a spring loaded device, receptors in muscles provide the human central nervous system (CNS) with information about motion and force. The CNS can relate both cues to estimate the spring stiffness, and use a change in perception of either or both of these two quantities as an indication of a stiffness change. Strategies relating the stiffness difference to the force difference and to the motion difference are both found in previous research.[2–4]

Different strategies could affect the level of noticeable stiffness difference, as the haptic force and motion difference thresholds of a human may not be the same. In the current work, we will investigate two strategies that humans could use for stiffness discrimination, namely the force strategy and the displacement strategy. The former definition means that humans discriminate between different stiffness levels on the basis of changes in the contact force when pushing the manipulator to the same amount of displacement. The later one consider the reverse, i.e., basing the stiffness discrimination on changes of manipulator displacement while trying to push the manipulator with the same amount of force.

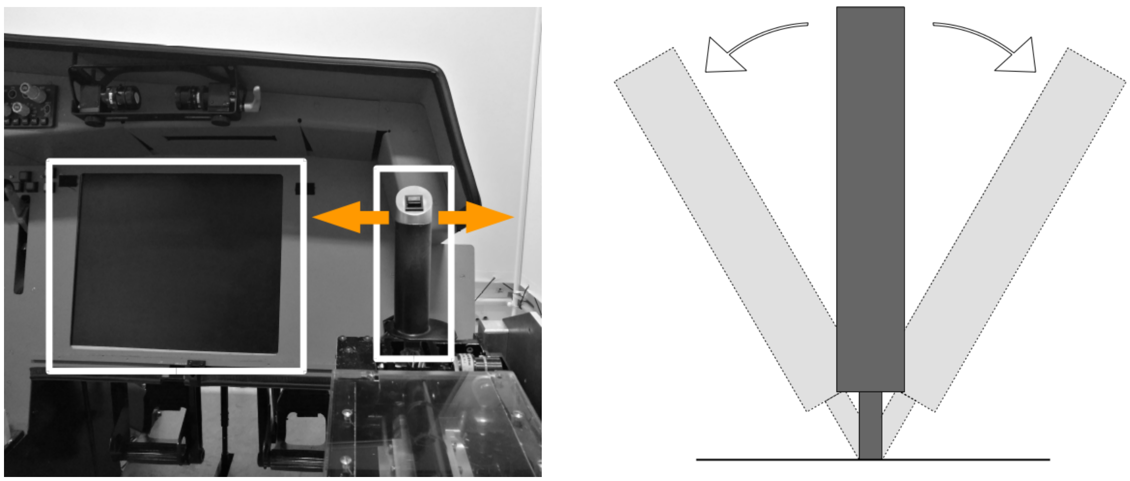
In order to find which of the two strategies yields a higher sensitivity to stiffness variations, we measured their resultant stiffness JNDs in two conditions independently. The stiffness JND was measured through a staircase stiffness discrimination procedure, during which our human subjects had to conduct a series of discrimination between different stiffness settings of a spring-loaded manipulator. The stiffness JND resulting from the force strategy was measured in the force condition, in which our subjects were instructed to match a fixed manipulator angular displacement and discriminate between different stiffness settings from differences in the contact force. Likewise in the displacement condition the displacement strategy was imposed, where subjects were asked to match a fixed contact force and compare different manipulator displacements. In addition to these two conditions, in another condition, which we referred to as the free condition, the stiffness JND were measured when no instructions on controlling either the contact force or manipulator displacement were given. Subjects were free to choose between the force strategy and the displacement strategy, or develop one involving both force and displacement changes. The JND measurement obtained from this condition was used as the reference to be compared with the results of the other two conditions. We also investigated the use of strategy in this condition by questioning subjects on the strategies they used for stiffness discrimination. To validate the conclusion of the investigation, we used two models respectively based on the force and displacement strategies to estimate the results of the free condition. Comparison between model estimates and experimental results were made to find the actual used strategy.

This paper is organized as follows: In the following section, the experiment procedure and conditions are described. In Section III the two models are elaborated. The results, analysis, and comparison of models are given in Section IV. We discuss the results and future work in Section V. Section VI concludes the contribution of this work.

II. Experiment setup and methodology

II.A. Apparatus

The experiment were performed in the Human-Machine Interaction Laboratory at the faculty of Aerospace Engineering, TU Delft. To simulate the desired stiffness setting, a side-stick manipulator with minimum mass and damper properties was used to generate an elastic force in response to its angular displacement. The manipulator could be only moved around the roll axis and was fixed in the pitch axis. An LCD screen was positioned in front of the subject, to indicate the timing of experimental runs, and also to provide the visual reference to assist our subjects to achieve the proper manipulator control. Subjects were asked to wear an active noise suppression headphone (David Clark H10-66XL), to cancel any possible auditory cue. An illustration of the devices can be seen in Fig. 2.



(a) (b)

Figure 2: An illustration of experimental devices. (a): The side-stick and the LCD screen are marked by rectangles. (b): The side-stick could be moved around the roll axis (left/right). The headphone used in the experiment is not shown in this figure.

II.B. Subjects

Seven subjects participated in the experiment. All were PhD students or academic staff from Delft University of Technology. They were all right-handed and reported no abnormality of the neuromuscular system or hand/arm impairment. An informed consent form was signed by subjects before the experiment.

II.C. Procedure

The difference threshold of a quantity is usually symmetric, which means the upper JND and the lower JND respectively defining the just noticeable increment and decrement of the quantity are roughly identical. Hence in this study we only measured the upper JND in stiffness. The measurement was obtained through a one up/two down weighted adaptive staircase procedure[5,6] that related the JND to 80.35% correct performance. An example of this complete procedure is shown in Fig. 3.

A complete staircase procedure generally contains about 20 trials. Each trial consists of two 5-second runs, and these two runs (one trial) compose a two-alternative forced-choice (2AFC) task. In one run the fixed reference stiffness setting (K_r, the stiffness level in which the JND is measured) is simulated, and an adjustable stiffness setting (the controlled stiffness $K_c = K_r + \delta K$, $\delta K > 0$) is simulated in the other run. The order in which the two settings are simulated is random and unknown to subjects. The interval between the two runs is 1.5 seconds. An illustration is shown in Fig. 4. In this paper, we define the run simulating the reference stiffness setting as the reference run, and the one simulating the controlled setting as the controlled run. After each trial, we ask our subjects to identify the controlled run, i.e., reporting the

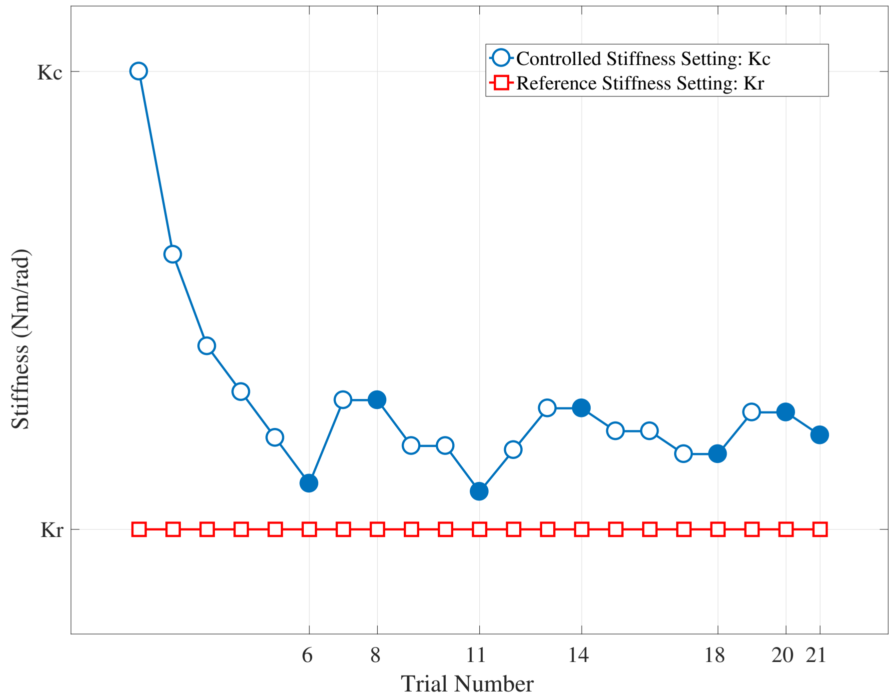


Figure 3: An example of the staircase procedure. The reference stiffness setting is fixed in the whole procedure. The controlled setting is always above the reference settings, and changes according to subjects' response. A one up/one down procedure is used before the first reversal for a quick convergence.

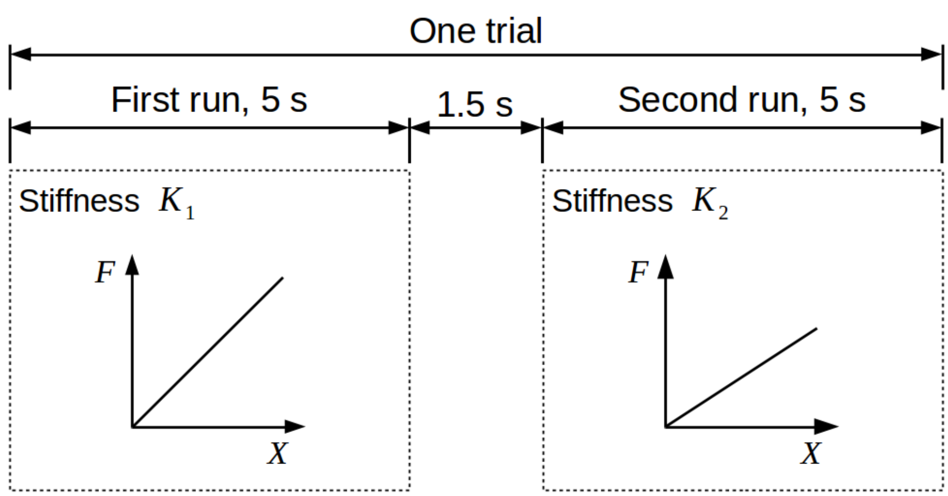


Figure 4: Procedure of each trial. The reference and controlled stiffness settings are simulated in a random order. In this figure, F and X represent the force applied to the manipulator and the manipulator displacement, respectively.

run in which the side-stick is felt stiffer. The controlled stiffness in the following trial is adjusted according to the subject's response. δK is reduced when a subject has provided correct answers for two consecutive trials and is increased after a wrong answer. A reversal represents a point where the staircase curve changes its direction (shown by solid circles in Fig. 3). A staircase procedure ends when the 7th reversal occurs, or when the total trial number reaches 40. The average of δK in the last four reversals is taken as the JND measurement.

Table 1: Conditions of the Experiment

Conditions	Reference Stiffness K_r (Nm/rad)	Fixed Variable	Compared Variable (Strategy)
Force	3.5	Displacement (0.37 rad)	Force
Displacement	3.5	Torque (1.295 $N \cdot m$)	Displacement
Free	3.5	-	Stiffness

II.D. Experimental conditions

Three conditions, which differed by the strategies used for stiffness discrimination, are defined respectively as the force, displacement and free conditions.

- The force condition (discriminate between forces).

  In this condition, the manipulator displacement was controlled. Subjects were instructed to apply a fixed stick displacement (0.37 rad) in the two runs in each trial, and were then asked to identify the run in which they perceived a higher force at this displacement. In this case, a stronger force reflects a stiffer spring (the controlled stiffness setting), and the stiffness difference in the following trial is adjusted according to the correctness of identification as discussed above. The stiffness JND measurements for this condition would indicate humans' best stiffness discrimination ability, if a force strategy is used.

- The displacement condition (discriminate between displacements).

  In this condition, we asked our subjects to apply the same amount of force (corresponds to a torque of 1.295 $N \cdot m$) in each run, and identify the run with a smaller stick displacement. With the same force applied, the smaller spring deflection indicates the stiffer spring. Thus identifying a smaller displacement in the controlled run contributes a correct answer. Similarly, the observed stiffness JND would suggest the best performance of the displacement strategy.

- The free condition (free comparison).

  In this condition, no variables were controlled. Subjects were required to report the run in which they experienced a stiffer spring. We asked our subjects to develop their own strategy for stiffness discrimination, and afterwards report the strategies they used.

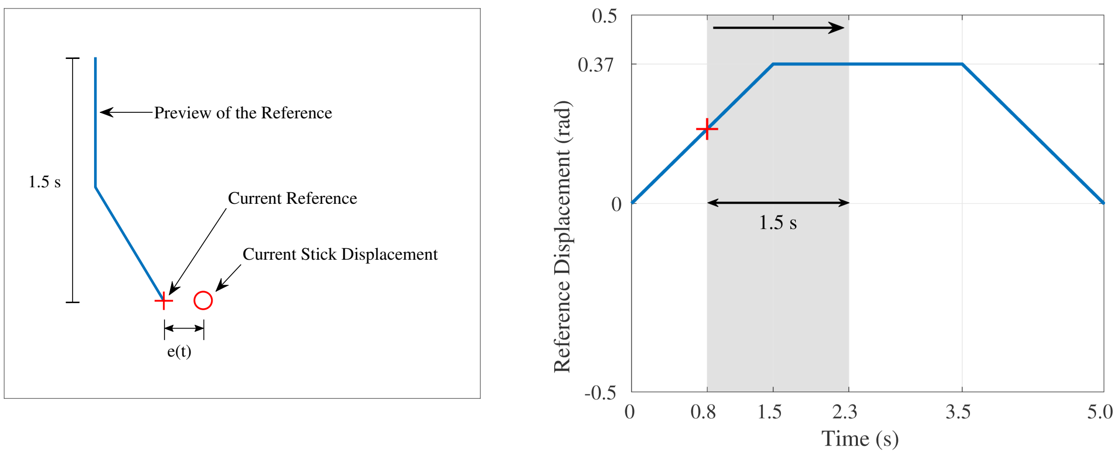
All the conditions were performed on a reference stiffness setting of 0.35 $N \cdot m/rad$. A summary of conditions is shown in Table 1.

II.E. Manipulator Control and Visual Display

In order to assist subjects to control the manipulator in the desired way (reproduce the right final displacement in the force condition and reproduce the right force in the displacement condition), we designed a tracking task during each run. In the force condition, the current and target stick displacement (fixed at 0.37 rad) were shown on a visual display, as shown in Fig. 5. We asked our subjects to track the target in each run in order to achieve the displacement reproduction.

A 1.5-second preview of the target stick displacement was shown on the display (Fig. 5a). The previewed target shown as a curve moved downward vertically across the display. The current target (+) is where the curve ends at the bottom. The current stick displacement was shown by an open circle. Participants were asked to reduce their tracking error $e(t)$ as well as they could. The reference side-stick displacement in each run is 0.37 rad as shown in Fig. 5b. The slow ramps in the first and last 1.5 seconds are used to reduce the force caused by the inertia and damping properties of the manipulator, which could affect the JND measurement. The reference displacement signal shown on the visual display is illustrated using the gray rectangle. It moves to the right when time progresses, in the same way as the reference curve shown on the visual display moves downwards.

In the displacement condition, a force tracking task was performed. This would guarantee that subjects apply a same amount of torque on the stick (1.295 $N \cdot m$) in each run. The display had exactly the same pattern as for the force condition, but with displacement cues replaced by force cues.



(a) (b)

Figure 5: The visual display (a) and the trajectory of the target side-stick displacement (b) in the force-condition experiment.

In the free condition, no reference was provided. We suggested our subjects to apply a similar motion pattern to the side stick (like a single push), to keep the perceptions in the three conditions being stimulated in the same frequency range.

III. Models

To models, namely the force model and the displacement model, are compared in their capability to characterize the behavior of subjects in the free-condition experiment. The force model estimates subjects' response by implementing the force strategy. Model estimates were based on the force data collected in the experiment. In each trial, this model identifies the run in which a larger force is observed as the controlled run. The displacement model estimates subject's behavior based on the displacement strategy. The run with a smaller stick displacement is considered as the controlled run, since this is the run simulating the stiffer spring.

In the experiment, we measured the torque instead of the contact force, using which in the force model does not affect the estimates since subjects did not change their grip point on the manipulator. We define $\{F_{1,i}, P_{1,i}\}$ and $\{F_{2,i}, P_{2,i}\}$ as the torque-displacement pairs for the two runs in the ith trial. An example is shown in Fig. 6.

Define ΔI_i as the criterion for models to select the controlled run, thus the force strategy can be formulated as:

$$\Delta I_i = F_{1,i} - F_{2,i} \quad , \quad \Delta I_i \begin{cases} \geq 0, \text{ select } R_{1,i} \\ < 0, \text{ select } R_{2,i} \end{cases} \quad , \tag{1}$$

in which $R_{1,i}$ and $R_{2,i}$ denote the first and second run respectively. Similarly, the displacement strategy can be expressed as:

$$\Delta I_i = P_{1,i} - P_{2,i} \quad , \quad \Delta I_i \begin{cases} \leq 0, \text{ select } R_{1,i} \\ > 0, \text{ select } R_{2,i} \end{cases} \tag{2}$$

Thus, given the force and displacement data, the two models could estimate a subject's response in each trial. The correspondence between the two model estimates and our subjects' actual responses would then indicate the plausibility of each model.

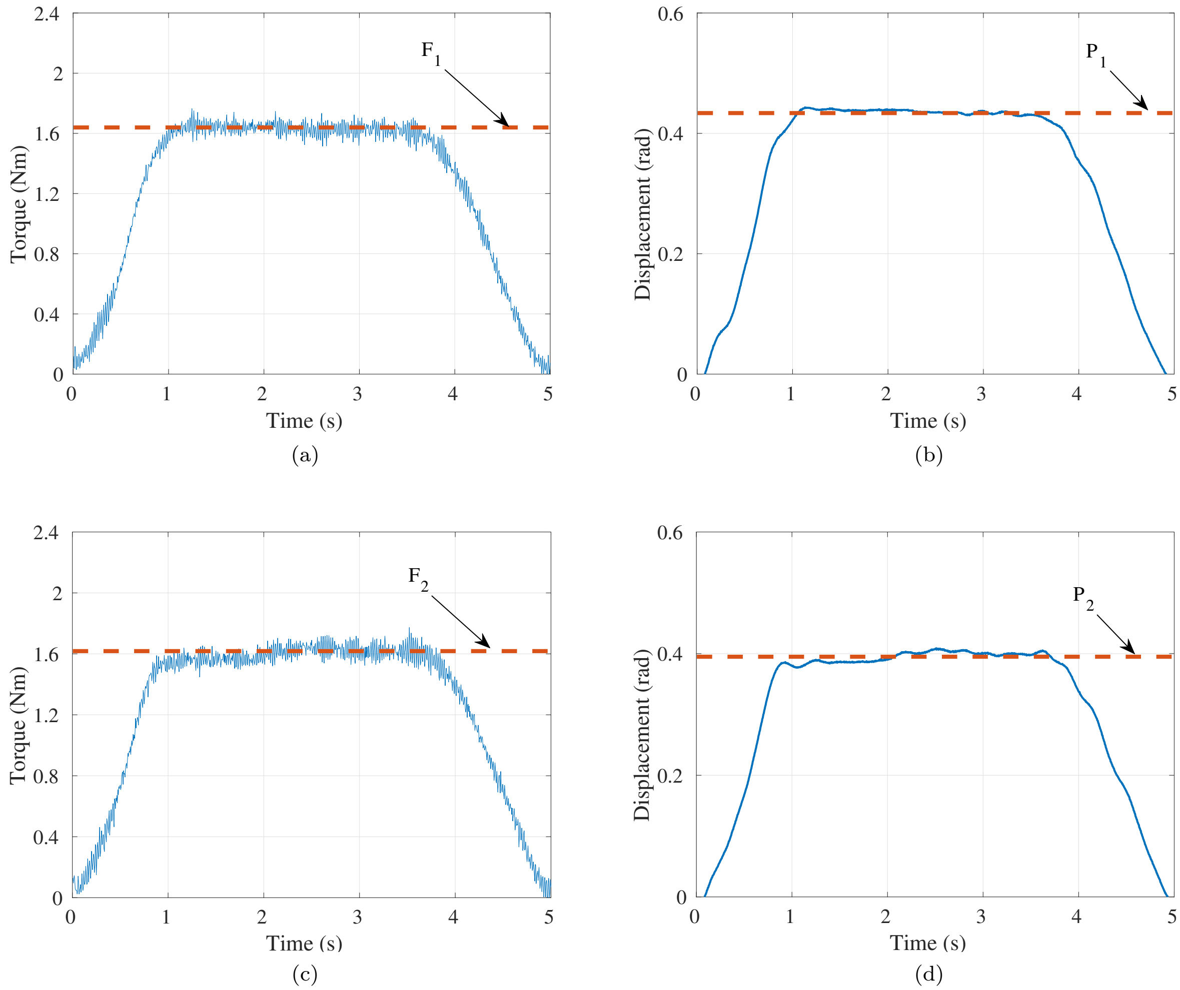


Figure 6: Side-stick forces and displacements applied by a subject in one trial in the free condition. F and P are obtained as the average of the stationary region, as shown by the red dashed lines.

IV. Results

IV.A. Result

The JND measurements for the three conditions are shown in Fig. 7. Here we express the stiffness JND as a fraction of the reference stiffness level (the Weber fraction). The stiffness JND observed for the displacement condition was $14.64\% \pm 6.16\%$, for the force condition it was $8.01\% \pm 2.72\%$, and for the free condition $10.28\% \pm 3.12\%$. A significant effect of different strategies was observed, one-way ANOVA: $F(2, 18)$=4.31, $p = 0.0295$. Posthoc t-tests revealed significance between the force and displacement conditions, $p = 0.0233$.

Apparently our subjects were less sensitive to stiffness variations when they were instructed to estimate stiffness differences from discriminating between different manipulator displacements. When they were instructed to compare forces for a fixed displacement, the lowest level of the stiffness JND were found. The observations in the free condition were in-between the results of the other two conditions. This implies that the choice of the strategy may not have been consistent among subjects, or that a different strategy was used. This will be investigated in more detail by questioning subjects on their strategies and using the model analysis.

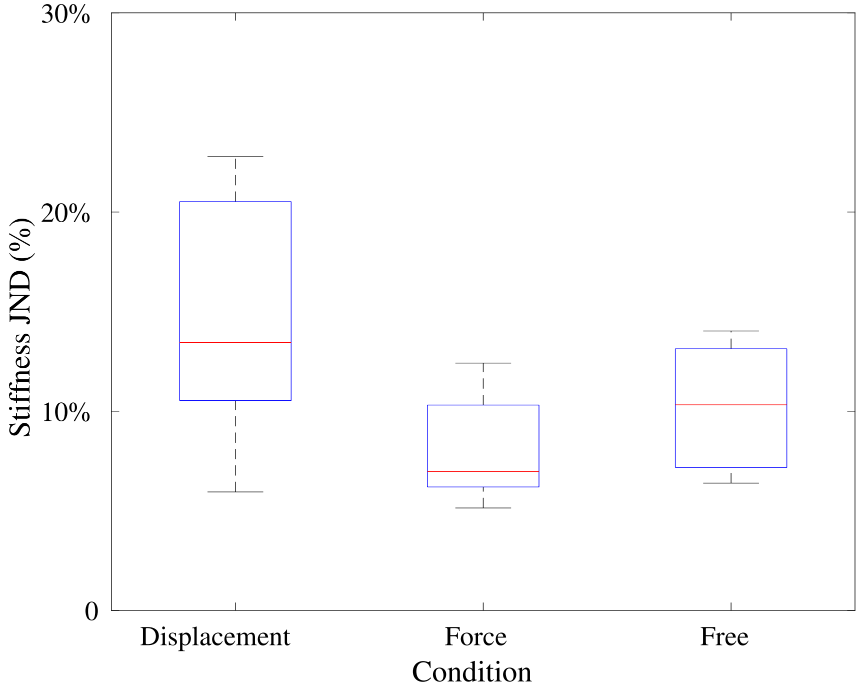


Figure 7: Boxplot of the JND measurements.

IV.B. Strategy Investigation

After the experiment, we interviewed subjects on their strategies for identifying the stiffer spring in the free condition. We found that all subjects based their selection of the stiffer spring on a force strategy. That is, to discriminate between two different stiffness levels subjects would try to reproduce the same amount of manipulator displacement (spring deflection) in the two runs, and use the force difference as the indication of the stiffness difference. An illustration of this process can be seen in Fig. 8. The process of stiffness

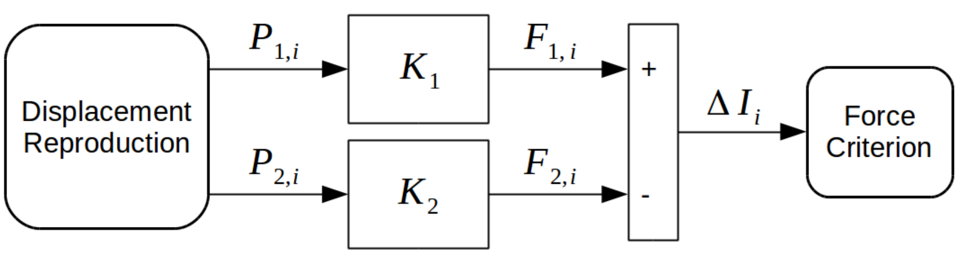


Figure 8: Stiffness discrimination process in the free-condition experiment.

discrimination in the free condition was the same as what was imposed in the force condition. The reason for the slight difference between results could be an inaccurate use of the force strategy.[2] That is, although our subjects intended to reproduce the side-stick displacement, without the visual presentation their accuracy was degraded. Define b_i as the displacement difference ratio for individual trials:

$$\Delta P_i = P_{c,i} - P_{r,i} \quad , \quad b_i = \frac{\Delta P_i}{P_{r,i}} \tag{3}$$

Here subscripts c and r denote the control run and reference run, i denotes the trial number. Define $N_b(E, \sigma)$ as the overall-subject distribution of b_i for trials after the third reversal. A good displacement control would result in zero mean and small variance of N, for example in the force condition these two quantities were -0.0005 and 0.03. For the free condition, the stick displacement in the control run (P_c) was smaller than that in the reference run (P_r) by 2% on average. A large variation $\sigma = 0.11$ was also observed.

This finding is consistent with the conclusion from our previous work.[2] The bias in displacement reproduction explains the difference in JND measurements found between these two conditions. A smaller deflection of the stiffer spring would generate a lower force difference, this makes the force comparison harder and a larger stiffness difference is thus required to provide a detectable force difference. This bias could be the result of a systematic error due to involving a force cue in human position estimates[7,8] used for a position reproduction.

IV.C. Model Validation

In order to validate the use of the force strategy in the free condition, we examined the correspondence of the model estimates to subjects' responses in a way similar to the work done in the perception of delayed stiffness.[9]

Define A_i as the response that a subject gives in the ith trial, and $\hat{A}_i$ is the response estimated by a model. We further define the proportion of trials in which a model's estimate agrees with the response of a subject ($A_i = \hat{A}_i$) as the agreement rate of the model:

$$C_i = \begin{cases} 1, & \text{if } \hat{A}_i = A_i \\ 0, & \text{if } \hat{A}_i \neq A_i \end{cases} \quad , \quad G = \frac{\sum_{i=1}^{i=N} C_i}{N} \tag{4}$$

Here G denotes the agreement rate of a model. N denotes the number of trials. The agreement rates of the force and displacement models are calculated for trials after the third reversal, as can be seen in Fig. 9.

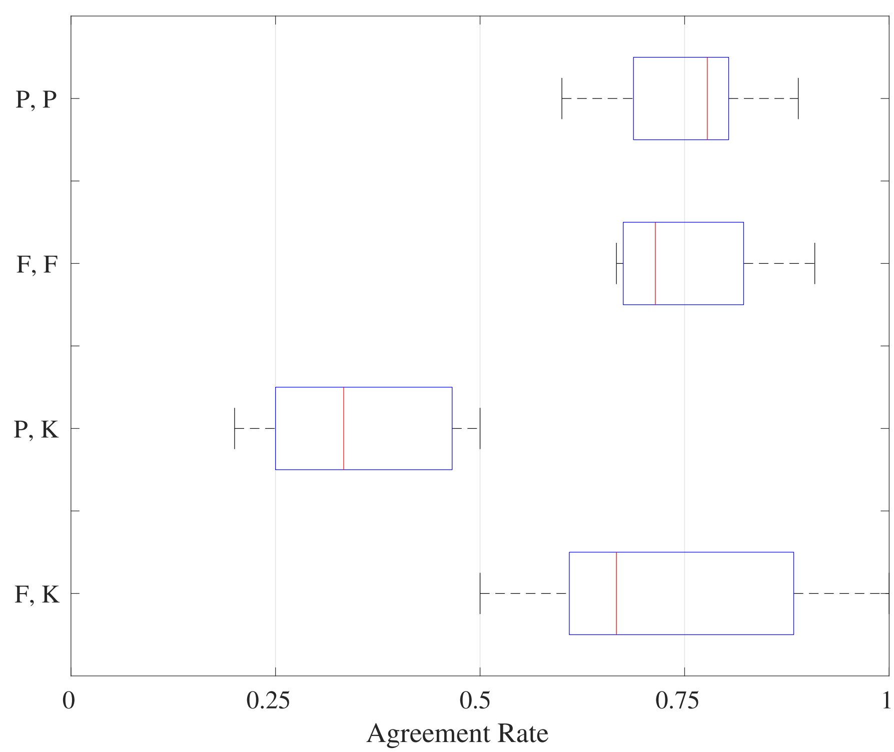


Figure 9: Agreement rate of each model. Boxplots represent the distribution of model agreement rates of subjects. The first terms in the labels of the vertical axis represent the strategy, with P for displacement and F for force. The second terms represent the condition, P, F and K are substitutions of displacement, force and free conditions respectively.

The agreement rates of the force model for the force condition and of the displacement model for the displacement condition are also calculated. This allows us to know the best correspondence between model estimates and experiment observations. As can be seen in Fig. 9, both rates indicate a non-perfect agreement and distribute around the level of 0.75. This is due to the wrong guess answers that resulted from unperceivable force or displacement differences.

The force model provides a similar agreement rate for the free condition. The average among subjects is 0.7338. The displacement model fails to provide an acceptable agreement. This indicates the plausibility of the force strategy over the displacement strategy, and is consistent with subjects' reported strategy.

V. Discussion

In the current work, we investigated two strategies that could provide humans with the information of stiffness differences, namely the force strategy and displacement strategy. There are also many other possible strategies that we have not included in the current work. For example an admittance strategy (comparing the manipulator velocity), which is difficult to be evaluated by the current experimental setting, and worth to be investigated in future work.

When subjects were forced to use a displacement strategy, the obtained stiffness JND was higher then that resulted from a force strategy. The large variation of the stiffness JND for this case also indicates a poor consistency among individuals. This indicates that this strategy could not result in an optimal and stable difference threshold for the perception of stiffness.

Subjects indicated that they used force differences for discriminating between different stiffness settings. The JND in the free condition was slightly larger than the JND found in the force condition, corresponding to earlier findings.[2] In the force condition, with the help of the visual presentation, subjects reached their lowest stiffness JND. The 8% Weber fraction reflects our subjects' limits to discriminate between different elastic forces. It is known that humans exhibit a similar difference threshold for elastic force and constant force.[3] This fraction (8%) is indeed in accordance to the force JND in literature.[10] With the current results, we would propose that the force JND indicates the humans' highest haptic resolution on stiffness. When evaluating the performance of CLS, one should therefore consider the force JND as the tolerance for the static response of the system.

VI. Conclusion

In the current work, two stiffness discrimination strategies, namely the force strategy and displacement strategy, and their resultant stiffness JNDs were investigated. We invited seven human subjects to participate in a stiffness JND experiment with three conditions. We related the stiffness JND to subjects' force difference threshold in the force condition, and in the displacement condition the stiffness JND was measured from subjects' displacement difference threshold. In the free condition, the stiffness JND were measured when no constraints were imposed on the choice of the strategy, which means both force and displacement changes could be used for the stiffness discrimination. Subjects were most sensitive to stiffness variations when the force strategy was imposed (the force condition). In the free condition, subjects indicated the use of the force strategy for stiffness discrimination. But the JND measurements were slightly higher due to the reduction of accuracy in their displacement reproduction. The displacement strategy resulted in the highest level of the stiffness JND and a poor consistency among subjects. Two models based on the two strategies estimated the behaviors of subjects in the free condition. One assumed the force-strategy based discrimination, the other assumed the basis as the displacement strategy. Comparison between model estimates and experimental results validated the conclusion on the strategy used in the free condition, and indicates that when free to apply their own strategy, subjects largely based their stiffness discrimination on the detection of force differences.

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