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DRAFT: KINESTHETIC PERCEPTUAL SYMMETRY IN BIMANUAL INTERACTIONS: AN EXPLORATORY STUDY

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ABSTRACT

In this paper, we present a study to explore the symmetry of kinesthetic perception. Our goal is to add to the growing literature that investigates haptics technologies for therapeutic and rehabilitative applications. To this end, we study how selective activation/deactivation of haptic (specifically force) feedback affects human perception during symmetric bimanual (two-handed) spatial tasks. We conducted a simple experiment where healthy individuals are tasked with stretching a virtual spring using two symmetrically located haptics devices that provide an equal amount of resistive forces on each hand while pulling the spring. In this experiment, we implement four kinesthetic conditions, namely (1) feedback on both hands, (2) feedback only on dominant hand, (3) feedback only on non-dominant hand, and (4) no feedback as our control. Our first goal was to determine if there exists a range of spring stiffness in which the individual incorrectly perceives bimanual forces when the feedback is deactivated on one hand. Subsequently, we also wanted to investigate what range of spring stiffness would lead to such perceptual illusions. Our studies show that not only does such a range exist, wide enough so as to be potentially utilized in future rehabilitative applications. Interestingly, we also observe that for few cases, symmetry can be independent of the kinesthetic perception.

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1 Introduction

In this paper we conduct an exploratory study to understand and quantify kinesthetic perception from the point of symmetric bi-manual actions. Haptics-based virtual environments and systems have gained a significant place in therapeutic and rehabilitative applications in the recent past [1–3]. For instance, from the viewpoint of neurorehabilitation, recent works [4–7] have broadly focused on recovering sensorimotor perceptions for patients suffering from hemiparesis — having partial to no mobility in either limbs. While there are works that discuss detailed research on motor recovery, sensorimotor perception is yet to be fully explored from the point of bi-manual actions, kinesthetic feedback, and proprioception. While hemiparesis is one example where the effects of kinesthetic perception is pronounced, there are several other conditions for which a fundamental understanding of kinesthetic feedback is useful. Our motivation to study how healthy individuals perceive force-feedback in symmetric bi-manual tasks is to draw a baseline for future exploration of kinesthetic symmetry for neurorehabilitation of upper limbs.

Our study is inspired by the mirror box therapy [8] that uses mirrored visual feedback for patients suffering with the phantom limb syndrome (wherein a subject feels pain and other sensations in a limb that has been amputated). While several studies [9–12] have been conducted to study how visual perception can alleviate conditions in phantom limbs, little is currently known about how kinesthetic feedback provides perceptual symmetry alleviating the phantom limb pain (PLP). Our goal in this paper is to explore the perceptual aspect of kinesthetic feedback for sensorimotor recovery focusing on symmetric bi-manual actions.

The objective of our experiment is (a) to determine if there is a difference in kinesthetic perceptual symmetry for a bi-manual spring pulling action when the force is selectively activated/deactivated on either hands, (b) to quantify kinesthetic perception in terms of a stiffness range which creates an illusion of symmetry irrespective of the force, and (c)finally, quantify an average distance between two hands for a bi-manual spring pulling action beyond which the kinesthetic perception tends towards asymmetry. In this paper, we currently restrict our study to healthy individuals.

In this paper, we make three main contributions. First, we identify that for cases when feedback on both hands are on or completely off, bi-manual symmetry is independent of kinesthetic perception. Second, we conduct a formal human subject evaluation to better understand the relationship between kinesthetic perceptual symmetry and increase in spring stiffness. Third, we identify a range of stiffness values that lead to the illusion of kinesthetic symmetry in bi-manual interactions irrespective of selective activation or deactivation of forces on either hands.

2 Related Work

2.1 Kinesthetic Perception

The notion of kinesthetic perception originates from the *sensation or stimuli experienced in the muscles, tendons, and joints* allowing us to experience the world around us through force, stiffness, and vibration [13, 14]. While the classic approach is to compare one's bodily orientation with the true vertical [15], recent works [16] have looked deeper into the inter-sensory cues (visual, vestibular, and proprioceptive) that help create awareness of one's position and orientation with regards to their surroundings. Expanding on this, early research on neurorehabilitation [17] emphasizes on kinesthetic perception being the most affected affordance of a person after a stroke. It is also one of the key components for assessing the level of brain injury in human post stroke. Building on similar thoughts, few recent works highlight different aspects of kinesthetic perception — active or passive so as to provide a physical support or kinesthetic illusion to aid with muscle level recuperation. Recently, several works [1–3, 7, 9, 18] have investigated kinesthetic perception in the context of sensorimotor recovery. A common theme in these works is to directly apply known kinesthetic training methodologies to study patients with snesorimotor impairment. One example is the work by Kutlay et al. [18] that investigates a kinesthetic ability test to improve unilateral neglect (a condition in which patients fail to report, respond or orient to meaningful stimuli presented on the affected side) in stroke patients. While these are seminal works, we believe that fundamental insight regarding how our brains and bodies process kinesthetic information would complement these approaches.

2.2 Stiffness-based Haptics Interventions

Stiffness is one of the key affordances in virtual environments that allows humans to experience the virtual world with a synthetic physical stimuli [19]. Stiffness-based force-feedback has been used in spatial interactions for creation [20, 21], exploration [22–27], and manipulation [28, 29] of objects in virtual environments. For rehabilitation, stiffness acts as a supporting as well as a resisting force helping patients regain motor capability caused due to hemiparesis or any brain related injuries. The primary applications have focused towards the broader spectrum of soft robotics mainly focused at exoskeletons [30–38] providing an *active* support to the physically impaired in order to help them regain muscle strength and recover their physical abilities. As stated by Parker et al. [17], kinesthetic recovery is effective only when patients attempt to perform tasks that they have been doing *normally* in their daily lives. However, stiffness as a kinesthetic feedback provides qualitative perception of support or resistance in virtual environments. One of our main goals in this paper is to develop a quantitative understanding of stiffness-based approaches in terms of the average force required for kinesthetic perception in joint-symmetric bi-manual tasks.

2.3 Bimanual Symmetric Actions

Mechsner et al. [39] discuss presence of both perceptual and spatial symmetry for bi-manual actions. This is opposed to the conventional view which suggests relation to co-activation of homologous muscles such as the upper limbs in this case. Further, Hatem et al. [40] review stroke related rehabilitation training focusing on non-invasive brain stimulation, robot-assisted training, and virtual reality immersion. They also provide a decision tree built upon the extensive literature and characteristics of stroke patients to propose a tailored rehabilitation approach. The review also mentions the need to study bi-manual coordination as preliminary studies showed better recovery, but need further exploration. Similarly, Latimer et al., [41] emphasized on effectiveness of bilateral training in post stroke recovery methods. Burgar et al. [42] supported the idea of bilateral training using the evidence that the *corticospinal ipsilateral pathways*, which are involved in recovery from hemiplegia are also found to be active in bilateral movements. Few works [43–45] discuss bimanual rehabilitation as a form of physical coupling where the unimpaired limb assists humans in rehabilitation of the impaired limb. This is because both the arms receive the same neural signal from the brain and they tend to move together in symmetric manner. One of the advantages of bimanual rehabilitation is that without externally constraining the affected upper limb, we can achieve benefits similar to that obtained from Constraint-Induced therapy. This view is also echoed in works by Latimer et al. [41] discussing that bilateral movements may utilize inter-hemispheric connections inside the brain to activate the damaged hemisphere. Malabet et al. [45] discussed three types of symmetric actions, namely joint space symmetry (JSS) — symmetry about the joints, virtual space symmetry (VSS) — symmetry along a cartesian axis, and point mirror symmetry (PMS) — rotational symmetry about a fixed point, out of which the most commonly used for bimanual rehabilitation is JSS. Several rehabilitation devices incorporate this symmetry for neurorehabilitation. Thus, it is important to understand the intersection between bimanual symmetric actions and kinesthetic feedback for rehabilitation training.

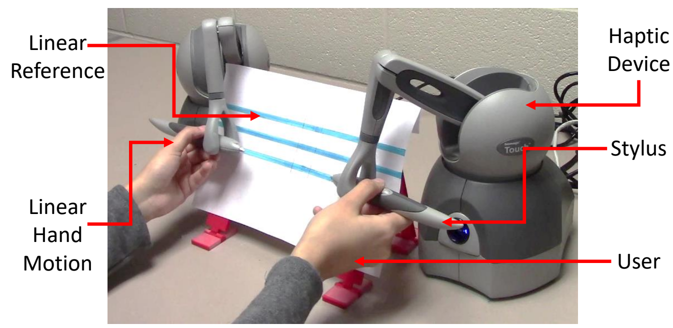

FIGURE 1. Study setup with two GeoMagic Touch haptic device and a visual reference for a linear spring motion.

2.4 Force-feedback in Rehabilitation

Haptic feedback and robots in tandem have been demonstrated as effective tools in physical rehabilitation training for stroke survivors [46–53]. Few works [54], [43] discuss portability of rehabilitation training using robotic systems away from medical centers after their initial treatment. These devices can be an economical and a faster way of recovery as the patients can devote more time for their therapy. They can also be customized in the terms of intensity of feedback depending on the functioning of subjects and stages of treatment. The novelty of AR/VR interfaces was explored by few works [1–3, 55] extensively discussing how mixed-reality approaches that are mainly visual based assist in neurorehabilitation training for sensorimotor recovery. Drawing inspiration from these works, we propose the use of haptics devices to study the changes in the kinesthetic perception for symmetric bimanual actions augmented by kinesthetic feedback.

3 Methods and Tools

In this paper, our primary intention is to explore and investigate kinesthetic perceptual symmetry in healthy human beings for bi-manual spatial interactions. We hypothesize that for a given range of stiffness values, bi-manual symmetry is retained despite variations in kinesthetic support. For this we discuss the setup configuration, design rationale, and the implementation aspects of the aforementioned hypothesis in the following sections.

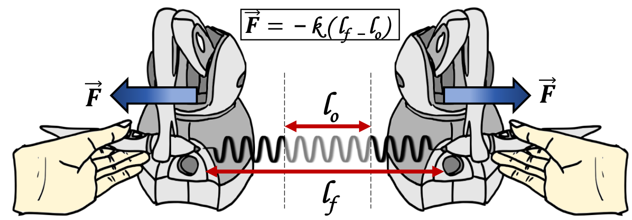

FIGURE 2. Symmetric force experienced by each hand on stretching a virtual spring.

3.1 Experimental Setup

Our setup (Fig. 1) comprises of two 6DoF GeoMagic Touch haptic devices placed parallel to each other with the styli acting as two ends of a virtual spring coil. In order to facilitate an axial motion of the spring, we provide a physical visual reference in the form of an illustrated line to encourage linear actions by the users. In addition, we configure the buttons on each styli to implement our interaction workflow. Further, we position the haptic devices to provide a comfortable interaction space to minimize hand-fatigue caused due to prolonged mid-air suspension.

3.2 Experimental Conditions

There are two primary input actions – *start* and *stop* activated by press and release of the forward button on each stylus to facilitate a resistive force (Fig. 2) on stretching the virtual spring. The styli are positioned initially at the ends of the virtual spring and the forward button is pressed to activate the resistive spring force. A resistive spring force, $\vec{F} = -(k \times \Delta x)$, is applied on the stylus when users stretched the virtual spring. Here, k is the spring stiffness and Δx is the total extension of the spring beyond its natural length i.e. $(l_f - l_0)$.

For the purposes of our study, we define four different conditions comprised of two symmetric and two asymmetric force feedback scenarios. The conditions are:

T1 Both Hands On: This treatment was assumed to be the ground truth (control) since both hands are symmetrically supported by equal and opposite kinesthetic feedback provided by each haptic device. Thus, both devices gave a force-feedback as a ground truth.

T2 Both Hands Off: In this case, neither of the haptic devices provided a force-feedback to the user's hands.

T3 Dominant Hand On: The dominant hand of the users was identified and the haptic device corresponding it was configured to provide a force-feedback for a given trial. The one corresponding to the non-dominant hand remained deactivated.

T4 Non-Dominant Hand On: Similar to **T3**, the device corresponding to the non-dominant hand of the user was configured to provide a force-feedback for a given trial. The one corresponding to the dominant hand remained deactivated.

3.3 Designing the Virtual Spring

To facilitate a spring-like kinesthetic resistance, the fundamental requirement is for the user to perceive a virtual spring in terms of the grasp and resistance force provided for a constant stiffness value. In case of the grasp, the styli are configured to be held along the axis of the virtual spring in order to minimize the torque created by any arbitrary orientation of each styli. This helps in reducing the kinesthetic perceptual bias created by the torque in addition to the resistive spring force. Further, the forward buttons on each styli are programmed to switch on the spring force-feedback during the stretching action, thus, providing continuous kinesthetic resistance. This combination of stylus configuration and button-press was designed to provide a simple and intuitive interface for our study participants.

The virtual spring (Fig. 2) is designed to be a helical spring having a natural length (l_0) of 3 cms with a maximum spring length (l_f) of 28 cms in stretched configuration. The measurements for the virtual spring were designed iteratively through pilot tests focused on reducing mid-air fatigue, and providing a comfortable spatial interaction experience for the users. This is also designed to prevent any perceptual notion of sagging for longer springs which may invoke a non-linear relationship between the spring force ($\vec{F}$) and the displacement (Δx) for a given stiffness value. Thus, we maintain a linear relation for the sake of perceptual and computational simplicity.

3.4 Software Implementation

Our experimental setup (Fig. 1) is comprised of an Alienware 15R3 laptop computer with an Intel Core i7-7700HQ CPU (2.6GHz), 16GB of GDDR5 RAM, and a NVIDIA GeForce GTX 1060 graphics card, running 64-bit Windows 10 Professional Operating System. Our application was developed in C++ with OpenGL and OpenHaptics libraries for haptic rendering.

4 Experimental Procedure

This experiment is designed with the hypothesis that there exists a range of spring stiffness for which users cannot differentiate between the reaction forces experienced on the two hands for bi-manual symmetric actions. We conducted a user study to bolster our argument.

4.1 Participants

We conducted this study with a group of 14 participants randomly sampled from undergraduate and graduate students recruited through university advertisement, out of which 5 volunteered for pilot testing. They belonged to an age group of 18 to 30 years old. According to the information collected from the participants prior to the study, only 1 of them had their left hand as the dominant hand, whereas, 14 participants had their right hand as the dominant hand. In addition, we noted if any of the participants suffered from any physical condition that would prevent them from performing bi-manual activities efficiently, thus, ensuring them to be in a good physical health during the study.

4.2 Evaluation Tasks

Our evaluation tasks are designed with three goals in mind: (a) to evaluate a range of spring stiffness in symmetric bi-manual tasks for which the force experienced by each arm is equal and opposite, (b) based on the stiffness range, we wanted to compare four testing conditions involving selectively activating or deactivating either of the haptic devices so as to identify the average stretched length of the virtual string i.e. distance between the hands where the users can start to perceive asymmetry across both of them, and (c) finally, to observe if kinesthetic perception encourages users to perform bi-manual symmetric actions in 3D space. Based on these goals we designed the following evaluation task for users to perform.

4.3 Pilot Testing

We conducted 5 pilot studies so as to finalize a stiffness range where the lowest stiffness is the maximum for which bi-manual symmetric actions are least affected for all four treatments; the maximum stiffness is the minimum which introduces asymmetry in the kinesthetic perception for bi-manual actions. Thus, a range of values for k from 0 to 10 was tested in the pilot studies and a final stiffness range from 5 to 9 was tested as discussed in subsequent study tasks.

4.4 Procedure

The study involved a simple task of holding the two styli, one per haptic device and move them in symmetrically opposite directions in a linear manner. The two styli were grasped to be along the axis of the virtual spring so as to avoid any physical effect (like torque) apart from the resistive spring force. Visual illustrations in form of a painted line were provided as a reference to maintain a linear motion. In all there were three lines separated height-wise to accommodate participants of varying physical anatomy as observed during the pilot studies. We randomized the sequence of spring stiffness and the four treatments across all trials to avoid any learning bias.

The study lasted approximately 30 minutes on average per participant and each trial took about 3 to 4 seconds on average without any intervention from the study coordinator. Each session started with a general introduction of the kinesthetic interface familiarizing the participants with the spring pulling action as well as the spring force-feedback. This was followed by a demographic questionnaire, and some pre-screening interview questions eliciting the participant's physical health to perform bi-manual actions as well as their dominant hand. At any point during the study, the participants were unaware of the treatments for which they

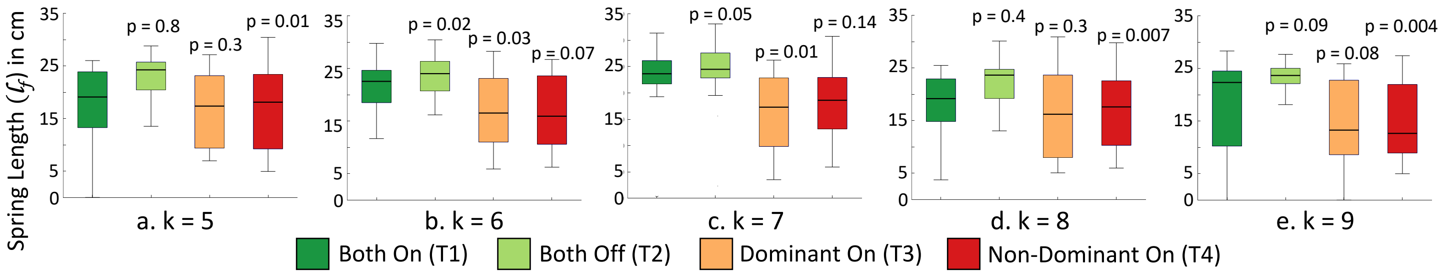

FIGURE 3. Stretched spring length in symmetric bi-manual actions compared across different treatments for each stiffness value. $p-values$ are measured from a pairwise comparison with the *Both On* treatment being the ground truth.

performed the trial and were simply asked to stretch a virtual spring as discussed in the following tasks:

Practice: The participants practiced using the virtual spring setup experiencing forces for maximum (k = 9) and minimum (k = 5) stiffness values. This was to familiarize them with the fact that the forces experienced during the study will fall between the boundaries of the maximum and minimum forces at a given distance.

Trials: We asked the participants to position their hands at the ends of the virtual spring illustrated by vertical lines in our study setup and start moving in symmetrically opposite directions when instructed. Each participant was asked to select the line they are comfortable to use as a reference and maintain the same selection across all trials. They were not allowed to rest their arms on the table as pilot studies confirm attenuation of the force-feedback experienced by the participants. Further, for a given stiffness value from the aforementioned range, we tested all four treatments in a randomized order for each participant. We asked each participant to notify at the instance when they felt forces acting on either or both hands depending on the individual. In cases where they did not feel any force, we instructed the participants to stretch until the maximum length of the illustrated reference line.

4.5 Data and Metrics

For each trial performed by a participant, we recorded the raw event log containing the (a) 3D position data for each styli, (b) force vector for each hand at each 3D position, (c) stiffness value for the current trial, and (d) time taken for the trial. The distance between two hands or the final stretched length (l_f) of the virtual spring is derived from the position data recorded in the event log and is used as a metric for comparison across stiffness and treatments. This distance helps in quantifying any asymmetry experienced for kinesthetic perception. Therefore, a relatively higher spring length (l_f) for a given stiffness value (k) and treatment (**T**) may reflect better kinesthetic perceptual symmetry with the underlying assumption that the participant is unable to detect any form of asymmetry in earlier stages of the study. Subsequently, a total of 27 trials per stiffness per condition was conducted and 540 trials overall were conducted for all 9 participants across 5 stiffness (k) variants and 4 treatments (**T**).

5 Results

In the following sections, we report on the statistical analysis of the stretched spring length (l_f), measured across five stiffness values and four treatments per stiffness. Further, we discuss the main insights gained from our data collection, observation, and user-feedback from all trials performed by all participants. First we present a pair-wise comparison (Fig. 3) of treatments **T2**, **T3**, and **T4** with **T1** being the ground truth. Subsequently, we shift our focus on comparing the effect of individual treatments (**T1, ... ,T4**) across different spring stiffness (Fig. 4).

5.1 Pairwise Comparison Across Stiffness

In this sub-section we take **T1** as the ground truth since both hands are kinesthetically supported through a continuous spring-based force feedback. Further, remaining treatments **T2, T3,** and **T4** are compared pairwise with the ground truth for a better understanding of kinesthetic perceptual symmetry in bi-manual actions by comparing distance between two hands; also known as the stretched spring length (l_f) at the instant where the participants experienced forces on both or either hands or maximum length of the illustrated reference line.

In order to evaluate l_f for each treatment with respect to the ground truth **T1**, we make the following hypotheses:

Null(H_o): There is no significant difference in mean stretched length $\overline{l_f}$ across different treatments for a stiffness value k.

Alternate(H_a): There is a significant difference in mean stretched length $\overline{l_f}$ across different treatments for a given stiffness value k.

Owing to our sample size, we assumed the data to be normal distribution. Further, we conducted a single factor pairwise

ANOVA for comparing treatments **T2** - *Both Devices Off*, **T3** - *Dominant Hand On*, and **T4** - *Non-Dominant Hand On* with **T1** - *Both Devices On* as the ground truth for a given stiffness value discussed as follows:

For $k = 5$:
A significant difference ($p = 0.01$) was observed for the pairwise comparison (Fig. 3(a)) between **T2** and **T1** where $\overline{l_f}$ for *Both Devices Off* treatment was found to be higher as 22.5 cms compared to the ground truth having 18.2 cms; with median distances of 24.2 cms and 19.1 cms for **T2** and **T1** respectively. While no significant difference was observed for treatments **T3** and **T4** with respect to the ground truth, a lower $\overline{l_f}$ was observed as 16.2 and 16.9 cms respectively.

For $k = 6$:
Significant differences were observed for pairwise comparisons (Fig. 3(b)) between **T3** ($p = 0.03$) and **T4** ($p = 0.02$) with respect to the ground truth. The $\overline{l_f}$ was found to be lower, 16.8 cms and 16.4 cms respectively compared to the ground truth having a mean distance of 20.6 cms; with median distances of 16.5 cms and 15.9 cms for **T3** and **T4** respectively. No significant difference was observed for pairwise comparison between **T2** and **T1**, but $\overline{l_f}$ were found to be 23.2 cms and 20.6 cms respectively.

For $k = 7$:
Similar to $k = 6$, significant differences were observed for pairwise comparisons (Fig. 3(c)) of **T3** ($p = 0.01$) and **T4** ($p = 0.05$) with respect to the ground truth. The $\overline{l_f}$ was found to be lower, 15.8 cms and 17.2 cms respectively compared to the ground truth having a mean distance of 21.4 cms; with median distances of 17.2 cms and 18.6 cms for **T3** and **T4** respectively.

For $k = 8$:
Similar to $k = 5$, significant difference ($p = 0.007$) was observed for the pairwise comparison (Fig. 3(d)) between **T2** and **T1** where $\overline{l_f}$ for *Both Devices Off* treatment was found to be higher as 22.3 cms compared to the ground truth having 18 cms; with median distances of 23.7 cms and 19.2 cms for **T2** and **T1** respectively. No significant difference was observed for treatments **T3** and **T4** with respect to the ground truth, a lower $\overline{l_f}$ was observed as 16 and 16.5 cms respectively.

For $k = 9$:
Again, similar to $k = 5$ and $k = 8$, significant difference ($p = 0.004$) was observed for the pairwise comparison (Fig. 3(e)) between **T2** and **T1** where the $\overline{l_f}$ was found to be 23.2 and 18.2 cms respectively; with median distances of 23.7 cms and 22.4 cms respectively. No significant difference was observed for treatments **T3** and **T4** with respect to the ground truth, a lower $\overline{l_f}$ was observed as 14.6 and 14.8 cms respectively.

5.2 Comparison Across Treatments

In this subsection we compare each treatment across different spring stiffness to observe any significant differences in stretched spring length $\overline{l_f}$ to identify perceptual asymmetry with increasing stiffness. Thus, we have the following hypotheses:

Null(H_o): There is no significant difference in mean stretched length $\overline{l_f}$ across different stiffness for a given treatment.

Alternate(H_a): There is a significant difference in mean stretched length $\overline{l_f}$ across different stiffness for a given treatment.

Akin to the pairwise comparison, we performed a single-factor ANOVA statistical test for comparing the mean stretched length $\overline{l_f}$ for a given treatment across five stiffness groups discussed as follows:

For **T1**:
No significant difference was observed across different stiffness groups (Fig. 4(a)) for the treatment when *Both Devices Stayed On* providing a force-feedback to both the hands of the user. However, $\overline{l_f}$ was observed to monotonically increase from $k = 5$ (18.2 cms) to $k = 7$ (21.4 cms); and decrease until $k = 8$ (18 cms) and $k = 9$ (18.2 cms).

For **T2**:
In this case too, no significant difference was observed across different stiffness values (Fig. 4(b)) for the treatment when *Both Devices Stayed Off* providing no force-feedback to either hands of the user. However, $\overline{l_f}$ was observed to increase from $k = 5$ (22.4 cms) until $k = 7$ (24.3 cms); and decrease until $k = 8$ (22.3 cms) and $k = 9$ (23.3 cms).

For **T3**:
Similar to **T1** and **T2**, no significant difference was observed across different stiffness values (Fig. 4(c)) for the treatment when *Device on Dominant Hand Stayed On* providing force-feedback to the dominant hand of the user. However, $\overline{l_f}$ was observed to be consistent from $k = 5$ (16.2 cms) until $k = 6$ (16.8 cms); and decrease until $k = 9$ (14.6 cms).

For **T4**:
Similar to previous treatments, no significant difference was observed across different stiffness values (Fig. 4(d)) for the treatment when *Device on Non-Dominant Hand Stayed On* providing force-feedback to the non-dominant hand of the user. However, $\overline{l_f}$ was observed to be consistent from $k = 5$ (16.9 cms) until $k = 8$ (16.5 cms); and decrease until $k = 9$ (14.8 cms).

5.3 User Feedback & Observations

We collected open-ended feedback on completion of stretching tasks from every participant. We discuss some relevant feedback in conjunction with our own observations during the tasks.

Kinesthetic Perceptual Symmetry
We designed our study setup to minimize any form of bias in the spring forces experienced by the user. This design was based on observations during the pilot study and was perceived well dur-

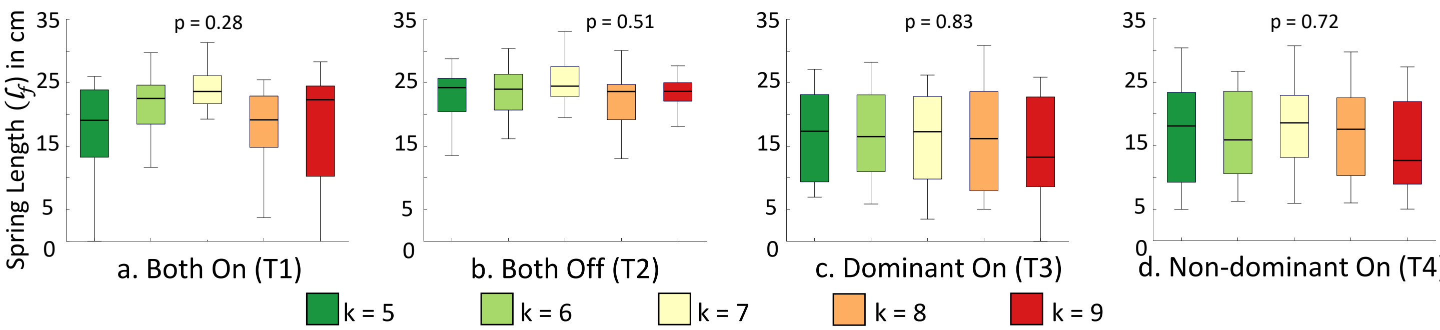

FIGURE 4. Stretched spring length in symmetric bi-manual actions compared across different stiffness values for each treatment type. $p - values$ are measured from a single factor ANOVA conducted for each treatment.

ing the actual trials giving a "*spring-like*" kinesthetic feedback to the participants. While we did not explicitly ask the participants to notify the hand in which they felt the force, most expressed in their feedback that some form of a "*difference*" in forces elicited their response to the study-coordinator. This explains the relatively lower stretched spring length (l_f) for treatments **T3** and **T4** compared to conditions where the feedback was either full on or off; where asymmetric forces for a certain stiffness k might caused the "*difference*" experienced by the participant. Another participant stated "*experiencing strain*" in one of their hands as a cue to asymmetric forces. One participant relied on the kinesthetic perception of their dominant hand for a symmetric bi-manual spring pulling action.

Learnability

We randomized stiffness and treatments to avoid any learning bias towards the force-feedback. However, few participants explicitly stated that they were able to perceive a kinesthetic feedback in either hands for higher magnitudes of force and couldn't do so for lower magnitudes. Only one participant claimed better perception of forces in each hand with successive trials. This explains the relatively longer stretched spring length l_f for treatments where the force-feedback was active for both hands or completely deactivated at lower stiffness value k.

Visual Guidance

Based on our pilot studies, we provided a visual guidance as an illustration of a line for maintaining a linear pulling action. We observed that most participants utilized the illustration as a visual reference for maintaining their motion in space, as well as it helped them imagine pulling a spring in addition to the force feedback. Few participants expressed discomfort post trials in using the lines as a reference. This was because the participant was more focused on maintaining a linear action such that they couldn't perceive the forces on either hands correctly.

Since, we didn't explicitly ask the participants to notify the hand where they felt the force; we believe the aforementioned feedbacks could be the reason behind false positives — misperception of the conditions applied by the study coordinator.

6 Concluding Remarks and Future Directions

Our primary goal in this paper was to explore kinesthetic perceptual symmetry in bi-manual actions. We conducted an exploratory study where participants were asked to pull a virtual spring while experiencing a resistive spring force. The intent was to identify a range of spring stiffness for which perceptual symmetry is unaffected by selective activation and deactivation of forces on either hands. For this, we tested four conditions from the viewpoint of symmetric and asymmetric force feedback and how they relate to spring stiffness, stretching distance, and kinesthetic perception of the participant. Our study revealed two interesting insights. First, we observed that symmetry in bimanual actions is unaffected by selective activation and deactivation of forces for treatments where force feedback is either completely on or completely off for both hands. This was supported by the evidence that mean stretched spring length ($\overline{l_f}$) for **T2** - *Both Devices Off* was observed to be relatively higher compared to **T1** - *Both Devices On*, which was our ground truth since both hands were supported by equal and opposite force-feedback. This gives an interesting insight that symmetry is ingrained in human perception with or without kinesthetic feedback for symmetric bi-manual actions. Second, we identified a stiffness range for healthy individuals where the distance to perceptual asymmetry was observed to decrease with increasing stiffness in bimanual actions across most treatments. We observed that users found it easy to identify forces in either hands at a given distance d for increasing stiffness k as compared to lower stiffness.

Our future goal is to create perceptual models for healthy individuals and study the same conditions for patients with sensorimotor control disorders. We posit that our method may lead to robust diagnosis tools by characterizing difference of response to asymmetric feedback between healthy and disabled individuals. Furthermore, we also seek to extend our approach to determine new rehabilitative and corrective measures for patients with conditions such as hemiparesis. While this was an exploratory study, these observations indicate a richer set of research directions to investigate kinesthetic perception for bi-manual actions.

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