Motoric and Perceptual Kinesthetic Symmetry in Bi-manual Interactions

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Bi-manual (two-handed) actions have shown notable success in rehabilitative and therapeutic applications from the point of motor symmetry. Recent studies have shown that symmetry in actions is attributed to sensorimotor perception than mere co-activation of homologous muscles. In this paper, we present a study of symmetric and asymmetric haptic (specifically force) feedback on human perception and motor action during bi-manual spatial tasks. To the best of our knowledge, ours is the first procedure to specifically test the perceptual aspect of bi-manual actions in contrast to other works that typically characterize the physical/bio-mechanical aspects. Thereby in our experiment, healthy individuals were tasked with stretching a virtual spring using two symmetrically located haptics devices that provide an equal amount of resistive force 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 bi-manual 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 analysis shows that not only does such a range exist, it is wide enough so as to be potentially utilized in future rehabilitative applications.

1 Introduction

Haptics-based virtual environments and systems have gained a significant place in therapeutic and rehabilitative applications in the recent past [1–5]. There are works that discuss detailed research on motor recovery [6, 7], however, sensorimotor perception is yet to be fully explored from the point of bi-manual actions, kinesthetic feedback, and proprioception. Taking hemiparesis (having partial to no mobility in either limbs) as an example, we find that current literature [?, 8–11] has typically explored symmetry from a bio-mechanical or physical perspective, and not necessarily from a perceptual perspective (how a person perceives symmetry in movement). Several conditions other than hemiparesis require a fundamental understanding of kinesthetic symmetry *as perceived* by a person.

Unlike physical movements, which are amenable to direct measurement (e.g. hand trajectory), the perception of kinesthetic symmetry is highly subjective; and therefore difficult to measure and analyze. To this end, our aim in this paper is to demonstrate a haptics-based methodology to measure, characterize, and evaluate kinesthetic perceptual symmetry in bi-manual actions. Using our methodology, we further study how healthy individuals perceive force-feedback in symmetric bi-manual tasks. This study is critical in order to draw a baseline for future exploration of kinesthetic symmetry in sensorimotor rehabilitation of upper limbs.

Our method is inspired by the mirror box therapy [12] where a mirror is used as a 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 [13–17] have been conducted to study how visual perception can alleviate conditions in phantom limbs, especially in the early stages, little is currently known about how kinesthetic feedback provides perceptual symmetry in 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.

In this paper we develop a haptics-based setup to simulate the process of bi-manual extension of a spring in mid-air. Using this setup, we conduct an experiment (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, to quantify an average distance between two hands for a bi-manual spring pulling action beyond which the kinesthetic perception tends towards asymmetry in perception and action. We restrict our study to healthy individuals, having little to no mobility issues in their upper limbs.

This paper presents a comprehensive account of our recently published exploratory study [18] of kinesthetic perceptual symmetry in bi-manual interactions. We make four main contributions highlighting some fundamental and key aspects of kinesthetic symmetry in bi-manual actions. First, we present a new detailed *analysis of motoric symmetry* where we study participants' bi-manual speed profiles (§5). This analysis reveals that regardless of the symmetry conditions, healthy individuals can maintain motoric symmetry. Second, we present a comparative analysis of users' self-reported *perceptual symmetry* (§6). Our analysis revealed that for cases when feedback on both hands are on or completely off, bi-manual symmetry is independent of kinesthetic perception. We also 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. Third, we conduct a qualitative evaluation from user feedback as well as a video analysis to better understand the relationship between kinesthetic perceptual symmetry and increase in spring stiffness (§7.4). Finally, we provide a detailed discussion on guidelines and better future strategies for evaluating bi-manual symmetric tasks (§8).

2 Related Work

We discuss existing research related to kinesthetic perceptual symmetry from the perspective of kinesthetic perception, stiffness-based haptic approaches, bi-manual symmetric actions, and force-feedback in rehabilitation in the following sections.

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 [19, 20]. While the classic approach is to compare one's bodily orientation with the true vertical [21], recent works [22] 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 the same, early research on neurorehabilitation [23] puts emphasis on kinesthetic perception being the most affected affordance in a person after a stroke. It is also one of the key components for assessing the level of brain injury in humans post stroke. Building on the same, few works have highlighted 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 have investigated kinesthetic perception in the context of sensorimotor recovery [1–5, 13, 24, 25]. A commonly followed practice across these works is to directly apply known kinesthetic training methodologies in order to study patients with sensorimotor impairment. A recent example by Kutlay et al. [24] investigates a kinesthetic ability test to improve unilateral neglect in stroke patients — a condition in which patients fail to report, respond or orient to meaningful stimuli presented on the affected side. While these are seminal works in sensorimotor rehabilitation using kinesthetic feedback, our work strives towards a fundamental insight regarding how our brains and bodies process kinesthetic information that would complement current rehabilitation approaches.

2.2 Stiffness-based Haptics Interventions

Our work draws from Gibson's conceptual framework of *Ecological Psychology* [26], which is predicated on the idea of *perceived affordance*, a property of human-object interaction that connects how we perceive objects and plan our actions. In our specific case, the stiffness of a spring can be integrated as a perceived affordance property in a virtual environment; to allow a user to experience the virtual world with a synthetic physical stimuli [27]. For instance, Di Luca et al. study the effect of asynchronization in visual and haptic feedback on spring compliance perception on virtual objects in augmented and virtual reality systems (AR/VR) — if a positive or negative lag in either sensory perceptions creates a perceptual illusion affecting the affordance of a spring-based object deformation task. Their findings conclude towards a more subjective assimilation of both sensory perceptions (visual and haptic) in humans leading to an increase or decrease in the perception of spring compliance — softness or hardness in virtual objects being deformed. Stiffness-based force-feedback or haptic compliance in general has been used in spatial interactions for creation [28, 29], exploration [30–35], and manipulation [36, 37] of objects in virtual environments.

In case of rehabilitation, stiffness acts as a support as well as a resistive force helping patients regain motor capability caused due to hemiparesis or any brain related injuries. One of the most common approach for rehabilitation utilizes soft robotics, specifically exoskeletons [38–49], that provide an *active* support to the physically impaired to help them regain muscle strength and recover their physical abilities. Xiloyannis et al. designed an exosuit that works on the arm to provide support for people with motor impairments. Their analysis of electromyographic signals for spatial actions with and without kinesthetic support shows a delay in the onset of muscular fatigue, thus, reducing physical effort exerted by a person [50]. In fact, this has also been shown in a studies by Mohanty et al., wherein adding kinesthetic feedback for spatial rotation resulted in lower fatigue according to the study participants [29, 51]. Parker et al. [23] note that attempting to perform daily tasks is an important factor that influences kinesthetic recovery. Having said this, stiffness-based haptic feedback needs to be properly contextualized. In this work, we achieve this by mapping the feedback to a bi-manual spring pulling tasks which can be associated with a real-world action. While stiffness-based feedback has been used in several studies, [27, 35, 52], we find that its analytical treatment is largely qualitative. 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 to elicit kinesthetic perception in joint-symmetric bi-manual tasks.

2.3 Bi-manual Symmetric Actions

Bi-manual actions have been found to have perceptual and spatial symmetry as discussed by Mechsner et al. [53]. This observation is contrary to the conventional view that suggests bi-manual actions being causal only to the kinesthetic attribute of *co-activation of homologous muscles* — symmetrically located muscles such as the upper limbs in our case. In fact, Woodworth discovered over a century ago that moving our right and left arms simultaneously is an *effortless task* and needs minimal initiation to make it happen [54]. While this is true, sensorimotor rehabilitation specifically for upper limbs have focused on the impaired (paretic) arm and the true potential of bi-manual symmetric actions is little explored [55]. Recent works have shown how *interlimb coordination*, specifically for hands, is affected after stroke [56–58]. Specifically, a stroke induces kinematic (motion) and kinetic (force) constraints in motor movements. Alternatively, Iosa et al. discuss visuomotor control as a fundamental diagnosis for stroke patients primarily evident in *coupled hand movements* [59]. In their systematic review of stroke related rehabilitation training approaches focused on non-invasive brain stimulation, robot-assisted training, and virtual reality immersion, Hatem et al. [60] propose a decision tree based on extensive literature and characteristics of stroke patients that helps propose a tailored rehabilitation approach for motor impairments. The review also emphasizes the need to further explore bi-manual coordination as results from preliminary studies have shown improved recovery for sensorimotor rehabilitation. Similarly, Latimer et al. [61] discusses the effectiveness of bilateral training in post stroke recovery methods to a moderate level of success, but emphasizes on further investigation. One of the initial discussions on bi-lateral training by Burgar et al. [62] showed evidence that the *corticospinal ipsilateral pathways*, which are involved in recovery from hemiplegia are also found to be active in bilateral movements, thus, potentially beneficial for motor recovery of upper limbs. Few works [63–65] discuss bi-manual rehabilitation as a form of physical coupling where the unimpaired limb assists humans in rehabilitation of the impaired limb. This is because both arms receive the same neural signal from the brain and they tend to move together in symmetry.

One of the potential advantages of bi-manual symmetric actions for rehabilitation is that we can achieve

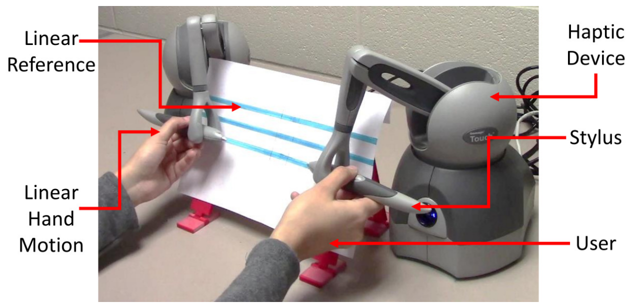

Fig. 1. Study setup with two GeoMagic Touch haptic device and a visual reference for a linear spring motion.

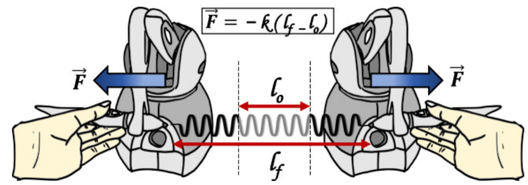

Fig. 2. Symmetric force experienced by each hand on stretching a virtual spring.

benefits similar to that obtained from *constraint-induced* therapy [66, 67] without externally constraining the affected upper limb. This view is also echoed in works discussing the role of bilateral movements in utilizing inter-hemispheric connections inside the brain to activate the damaged hemisphere [61]. On similar lines, Malabet et al. [65] discuss 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 bi-manual rehabilitation is JSS. In the same spirit, prior works [53, 68] have shown evidence about how asymmetry in hand motions eventually leads to JSS; sub-consciously through symmetry perceived in the mind, thus, overcoming the perceptual dissonance caused by asymmetric movements. These observations primarily are qualitative in nature with limited quantitative information, and therefore, it is important to understand the intersection between bi-manual symmetric actions, as well as, kinesthetic feedback for rehabilitation training.

2.4 Kinesthetic-feedback in Rehabilitation

Kinesthetic feedback influences a wide spectrum of spatial actions from coarse to fine manipulations by stimulating different parts of the upper limbs such as shoulders, elbows, palm, and fingers [69–75]. As a case in point, kinesthetic feedback is also a popular and recognized approach for rehabilitative tasks in the upper limbs [76, 77]. Generally, force-feedback enabled robotic prosthetic have been effective tools in physical rehabilitation training for stroke survivors [78–85]. Few works [63, 86] discuss the portability aspect of rehabilitation training in order to use robotic systems away from medical centers after the initial treatment phase. These devices can be economical as well as a relatively quicker way for patient-recovery as more time can be spent towards post-recovery treatments such as therapy. In addition, the home-based treatment 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 has been moderately explored by few works [1–3, 87] wherein mixed-reality (MR) approaches that are primarily visual, assist in neurorehabilitation training for sensorimotor recovery. In fact, Iosa et al. discuss the importance of visual feedback for *in-phase* and *out-phase* bi-manual actions in diagnosing post stroke interlimb coordination dissonance [59]. Similarly, Regazzoni et al. [88] propose a VR based framework relevant for prosthesis design and rehabilitative applications. These works lay the foundation for integrating kinesthetic feedback with MR systems towards effective sensorimotor recovery training. We draw our inspiration from the aforementioned research and propose the use of haptics devices to study the changes in the kinesthetic perception for symmetric bi-manual 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 (force-feedback). Our idea for quantifying kinesthetic perception with respect to healthy participants is to draw a baseline for future validation with patients suffering from partial to full paralysis. We discuss the setup configuration, design rationale, and the implementation aspects of the aforementioned hypothesis in the following sections.

3.1 Setup Design

Our setup (Fig. 1) comprises of two 6DoF GeoMagic Touch haptic devices placed parallel to each other with the styli facing the user and their tips acting as two ends of a virtual spring coil providing kinesthetic spring resistance. The devices are placed such that they align with the user's shoulder for a comfortable spring stretching experience and interaction distance, also, to minimize hand-fatigue caused due to prolonged mid-air suspension. In order to facilitate the spring displacement vector along its axis, 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.

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 in order to initiate a resistive force (Fig. 2) on stretching the virtual spring. The styli tips are positioned such that they represent the ends of the virtual spring and the forward buttons activate the resistive spring force when pressed simultaneously. A resistive force computed as, $\vec{F} = -(k \times \Delta x)$ is applied on each stylus in the direction opposite to user motion when stretched. 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 purpose 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: We assume this treatment 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 were force-enabled 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 to 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 due to torque which may affect the true perception of 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.

The virtual spring (Fig. 2) is designed to be a helical spring having a natural length (l_0) of 3 cm with a maximum spring length (l_f) of 28 cm in the stretched configuration. These 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. We discovered that the OpenHaptics library did not allow the use of two haptic devices simultaneously in a single CPU thread. Therefore, in order to simplify our implementation and avoid multithreading, we chose to use standard graphics loop provided by Open GL. This enabled robust and simultaneous haptic rendering across both haptic devices at a rate of 1000 Hz per device.

4 Experimental Procedure

We hypothesize the existence of a range of spring stiffness for which users cannot differentiate between the reaction forces experienced on the two hands for bimanual symmetric actions. We conducted the following study (TAMU IRB2017 − 0847D) to test our hypotheses.

4.1 Participants

We recruited 14 participants randomly sampled from undergraduate and graduate students recruited through university advertisement, out of which 5 volunteered for pilot testing. These participants were within the 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, 13 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) to compare (across different stiffness values) 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. For this, we first conducted a pilot study to identify a range for spring stiffness values that create a perceptual illusion of kinesthetic symmetry followed by a controlled lab experiment to characterize motoric and perceptual asymmetry in bi-manual actions.

4.3 Pilot Testing

With 5 participants, we conducted our pilot studies in order 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. We tested for a stiffness range k from 0 N/m to 10 N/m in the pilot studies and finalized k values from 5 N/m to 9 N/m 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 (Fig. 1) 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 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 for proper application of selection activation/ deactivation experiment controls. At any point during the study, the participants were unaware of the treatments for which they 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 the participants with the fact that forces experienced during the study will fall between the boundaries of the maximum and minimum stiffness at a given distance. Also, the intent was to provide a perceptual reference to the participants while performing the experiment task.

Trials: We asked the participants to position their hands at the ends of the virtual spring illustrated by vertical lines in our visual reference 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 confirmed 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 asymmetric 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 the virtual spring until the maximum length of the illustrated reference line.

4.5 Data and Metrics

In this experiment, we analyze, observe, and evaluate the spring pulling action from the perspective of *motoric symmetry* — symmetry in the action taken by the user (comparative movements of the two hands), and *perceptual symmetry* — symmetry in mental perception (when the user sensed asymmetry in the spring force-feedback between the two hands). For symmetry in action, we first conduct a cross-correlation time-series analysis [89] for speed trajectories of the left and right limbs per trial across all users. We validate this analysis using the normalized *Pearson cross-correlation coefficient* (r) as our metric [90]. The cross-correlation analysis in our case helps establish if the motion for either of users' limbs during bi-manual spring pulling actions is dependent on the other i.e. if motor symmetry is perceived synchronously during the study task. The underlying assumption for bi-manual symmetric actions is to have the same temporal effort across both limbs while pulling the virtual spring, however, it is difficult to maintain an exact symmetric motion in 3D space without an external support (§. 2.2). Therefore, the motion for each limb might be dissimilar with respect to the other at some instance of time during each study trial, and cross correlation analysis takes this into consideration so as to identify any deviation from symmetric bi-manual motion using the Pearson correlation co-efficient and lag between the two time-series speed data. We evaluate *perceptual symmetry* by statistically analyzing the stretched spring length (l_f) that highlights the interlimb separation for the hands at which users identified the onset of asymmetry in forces. The statistical comparisons for motor and perceptual symmetry are performed, (a) *across all experimental conditions for a given stiffness value*, and (b) *across all stiffness values for a given experiment condition*.

We independently sampled each trials performed by all participants. For each trial, the raw event log consisted of (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. Speed data was derived from the position data as well by computing rate of change of position between two successive data frames temporally separated by 0.001 seconds based on the device's 1000 Hz refresh rate. We hypothesized that the speed for both hands decreases with increasing stiffness due to increase in resistance for all four experiment conditions. During the course of this experiment, a total of 27 trials per stiffness per condition were conducted and 540 trials overall were conducted for all 9 participants across 5 stiffness (k) variants and 4 experimental conditions.

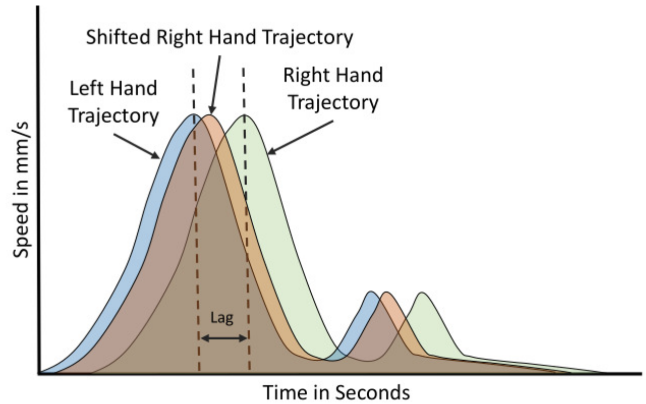

Fig. 3. Illustration describing *Normalized Cross-Correlation Analysis* [89] validating interlimb coordination and interdependency for bi-manual symmetric spring pulling action. While the algorithm automatically shifts either trajectories, the above depiction is for one possible scenario.

5 Results: Motoric Symmetry

In the following sub-sections, we report on our statistical evaluation for normalized cross-correlation time-series analysis [89] of the speed data between the left and right hands measured across five stiffness values and four treatments per stiffness. The cross-correlation analysis in our case serves as a preliminary validation approach to ensure the presence of motoric symmetry in bi-manual symmetric actions by confirming synchronization, as well as, the amount of interlimb lag (whether the hands started moving at the same time instance). We compare the speed trajectories for the left and right limbs using normalized Pearson cross-correlation coefficient metric (r) across all 540 trials (Figure. 3). A coefficient value close to 1 represents higher correlation, whereas, a value close to 0 represents poor correlation between the left and right limb speed trajectories. In our analysis, we considered any value of $r > 0.5$ as a stronger correlation between the motion of the upper limbs. First we present a pair-wise comparison 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 for speed and acceleration data respectively.

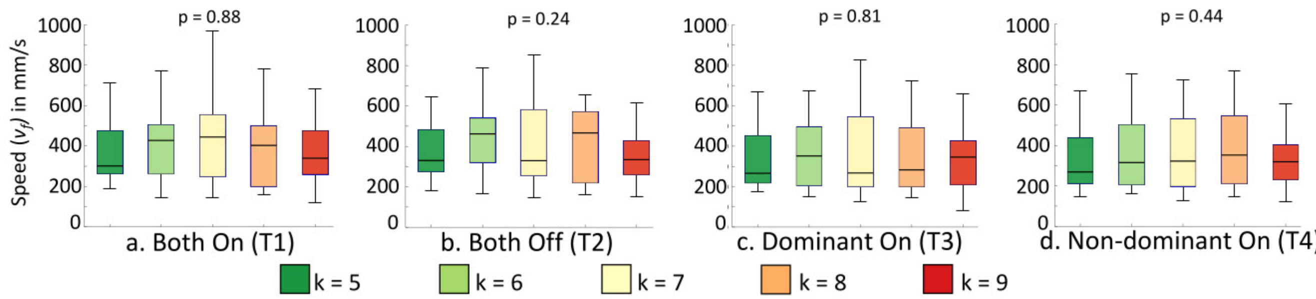

Fig. 4. Pearson correlation coefficient on comparing *speed* trajectories between left and right limb for symmetric bi-manual actions compared across different treatments for each stiffness value. $p - values$ are measured from a pairwise comparison with the *Both On* treatment being the ground truth.

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 controls such as **T2, T3,** and **T4** are compared pairwise with the ground truth for a better understanding of motoric symmetry in bi-manual actions. We make the following hypotheses in order to evaluate motoric symmetry pairwise for each treatment with respect to the ground truth **T1**:

Null(H_o): There is no significant difference in the mean cross-correlation coefficient (r) across different treatments for a given stiffness value k.

Alternate(H_a): There is a significant difference in the mean cross-correlation coefficient (r) across different treatments for a given stiffness value k.

Owing to our sample size, we assumed the data to be normally distributed and further 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:

For $k = 5$ N/m:
We didn't observe a statistical significance (Fig. 4 (a)) across all pairwise comparisons with the **T1**. However, the mean correlation coefficient was approximately same across all conditions — **T1** (0.85) followed by **T2** (0.88), **T3** (0.83), and **T4** (0.83).
For $k = 6$ N/m:
In this case no statistical significance (Fig. 4 (b)) was observed across all pairwise comparisons with the **T1**. Similar to previous stiffness, the mean correlation coefficient was approximately same across all conditions — **T1** (0.85) followed by **T2** (0.88), **T3** (0.85), and **T4** (0.83).
For $k = 7$ N/m:
Again, we didn't observe any statistical significance (Fig. 4 (c)) across all pairwise comparisons with the **T1**. The mean correlation coefficient was approximately same across all conditions — **T1** (0.85) followed by **T2** (0.88), **T3** (0.82), and **T4** (0.83).
For $k = 8$ N/m:
We didn't observe a statistical significance (Fig. 4 (d)) across all pairwise comparisons with the **T1**. However, the mean correlation coefficient was approximately same across all conditions — **T1** (0.82) followed by **T2** (0.87), **T3** (0.81), and **T4** (0.83).
For $k = 9$ N/m:
In this case as well no statistical significance (Fig. 4 (e)) was observed across all pairwise comparisons with the **T1**. Similar to previous stiffness, the mean correlation coefficient was approximately same across all conditions — **T1** (0.81) followed by **T2** (0.85), **T3** (0.78), and **T4** (0.82).

While we didn't achieve statistical significance, we made three key observations from the mean Pearson cross-correlation coefficient (r) trends with increasing stiffness'. First, we observe consistently higher mean cross-correlation coefficient for conditions where both devices were on and off (**T1 and T2**) respectively. Second, the condition where device on the non-dominant hand was on (**T4**) had a relatively higher mean cross-correlation coefficient than the condition where the device on the non-dominant hand was off (**T3**). Third, the mean cross-correlation coefficients for all conditions remain higher from stiffness values (k) of 5 N/m to 7 N/m and then decrease until 9 N/m, thus, confirming our hypothesis of increase in resistance causing an early onset of asymmetry in bi-manual hand motion trajectories. Overall, a higher Pearson cross-correlation coefficient value close to 0.8 was observed across all stiffness values and experiment conditions, thus, validating interlimb coordination between the left and right limbs in symmetric bi-manual spring pulling action.

5.2 Comparison Across Treatments

In this subsection we compare each treatment across different spring stiffness to observe any significant differences in Pearson cross-correlation coefficient values (r) for speed trajectories of the upper limbs. We make the following hypotheses:

Null(H_o): There is no significant difference in the mean cross-correlation coefficient (r) across different stiffness for a given experimental control.

Alternate(H_a): There is a significant difference in the mean cross-correlation coefficient (r) across different stiffness for a given experimental control.

Similar to the pairwise comparison across stiffness', we performed a single-factor ANOVA statistical test for the mean Pearson cross-correlation coefficient values (r) for a given treatment across five stiffness groups.

For **T1**:
No significant difference was observed across all stiffness groups (Fig. 5(a)) for the treatment when *Both Devices Stayed On* providing a force-feedback to both the hands of the user. However, the mean cross-correlation coefficient values observed across stiffness were decreasing with increasing stiffness: $k = 5$ (0.85), $k = 6$ (0.85), $k = 7$ (0.85), $k = 8$ (0.82), and $k = 9$ (0.81).
For **T2**:
Similar to previous treatment, no significant difference was observed across all stiffness groups (Fig. 5(b)) for the treatment when *Both Devices Stayed Off* i.e. no force-feedback was provided to either hands of the user. However, in this scenario, the mean cross-correlation coefficient values observed across stiffness were similar across all stiffness values: $k = 5$ (0.88), $k = 6$ (0.87), $k = 7$ (0.88), $k = 8$ (0.87), and $k = 9$ (0.86).
For **T3**:
Again, no significant difference was observed across all stiffness groups (Fig. 5(c)) for the treatment when *Device on the Dominant Hand Stayed On* providing force-feedback to the dominant hand of the user. Here as well, the mean cross-correlation coefficient values observed across stiffness were similar across all stiffness values: $k = 5$ (0.83), $k = 6$ (0.85), $k = 7$ (0.83), $k = 8$ (0.83), and $k = 9$ (0.82).
For **T4**:
No significant difference was observed across all stiffness groups (Fig. 5(a)) for the treatment when *Device on the Non-Dominant Hand Stayed On* providing force-feedback to the non-dominant hand of the user. However, the mean cross-correlation coefficient values observed across stiffness were decreasing with increasing stiffness: $k = 5$ (0.83), $k = 6$ (0.83), $k = 7$ (0.82), $k = 8$ (0.8), and $k = 9$ (0.78).

Overall, we made two key observations in these sets of comparisons. First, for a given experiment control, the interquartile range (IQR) for the box-plots increases with increasing stiffness, thus, depicting a larger spread for correlation coefficients which indicates the variation in perceptual illusions of asymmetry. Second, the mean correlation coefficients for a given condition start decreasing from k = 8 N/m to 9 N/m.

We also computed the lag between the left and right limbs across users using the cross-correlation analysis for comparison. On comparing for different stiffness and experimental controls, we found the lag to be infinitesimally low (close to zero), thus, confirming a near symmetric and synchronized bi-manual motion.

6 Results: Perceptual Symmetry

In the following sub-sections, we report on the statistical analysis of the stretched spring length (l_f), measured across five stiffness values and four treatments per stiffness. Similar to our statistical procedure for studying motoric symmetry, we present a pair-wise comparison 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.

6.1 Pairwise Comparison Across Stiffness

In this sub-section we take **T1** as the ground truth and it is compared pairwise with remaining treatments **T2, T3,** and **T4** 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 hypothesize:

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

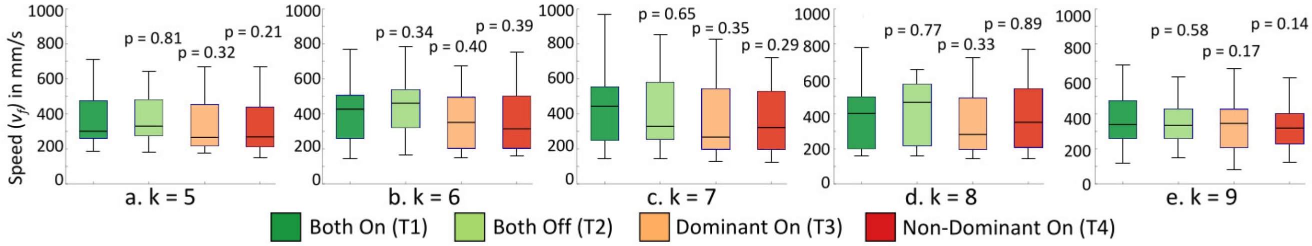

Fig. 5. Pearson correlation coefficient on comparing **speed** trajectories between left and right limb for symmetric bi-manual actions compared across different stiffness values for each treatment type. $p-values$ are measured from a single factor ANOVA conducted for each treatment.

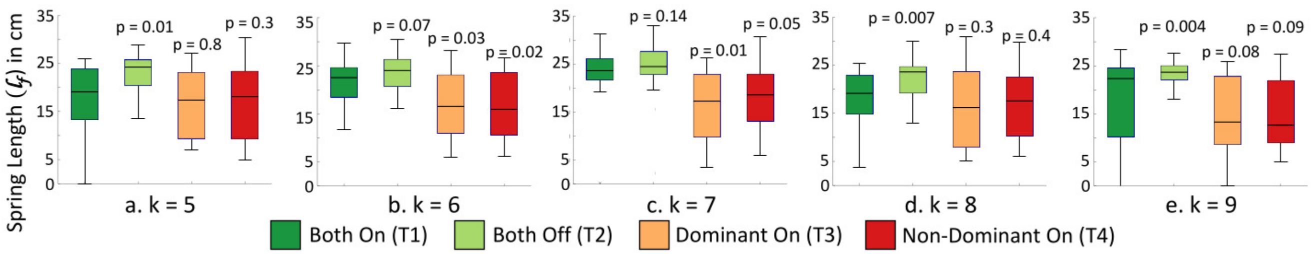

Fig. 6. Stretched spring length for symmetric bi-manual actions compared across different treatments for each stiffness value. $p-values$ are measured from a pairwise comparison with the *Both On* treatment being the ground truth.

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.

Similar to our previous analyses, 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. 6(a)) between **T2** and **T1** where $\overline{l_f}$ for *Both Devices Off* treatment was found to be as high as 22.5 cms when 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. 6(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. 6(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. 6(d)) between **T2** and **T1** where $\overline{l_f}$ for *Both Devices Off* treatment was found to be 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. 6(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.

Overall, we observe that participants typically stretched the virtual spring until the maximum length for the *Both Devices Off* (**T2**) condition followed by *Both Devices On* (**T1**) condition, thus, providing an insight into perceptual symmetry being present in the mind without an external kinesthetic stimuli, also confirmed by our analysis of motoric symmetry across different conditions for a given stiffness value (§. 5.1). The shorter stretched spring length (l_f) for conditions where the devices were selectively activated on dominant and non-dominant hands of the user could be attributed to the early onset of asymmetry in forces.

6.2 Comparison Across Treatments

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.

For this comparison as well, 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. 7(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. 7(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. 7(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. 7(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).

In this comparison scheme, we observed the onset of asymmetry in force-feedback occurred at similar distances across different spring stiffness (k) for a given experimental control. This gradual shift of perceptual asymmetry in forces was more pronounced with shorter stretched spring length (l_f) in conditions where the haptic devices were selectively activated for either hands (Fig. 7). Also, observed during our analysis of motoric symmetry across treatments (§. 5).

7 User Feedback & Video Analysis

In our final qualitative analysis, we first aim to report the users' feedback on the bi-manual symmetric spring pulling task and their experience with the kinesthetic feedback. We supplement this with a detailed video analysis to report on what types of movement patterns, kinesthetic cues, and user behavior were observed during the stiffness-based bi-manual task across 5 stiffness values and 4 experiment conditions. We discuss some relevant feedback in conjunction with our own observations during the tasks.

7.1 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 made during the pilot study and was perceived well during 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. In fact, the pursuit of identifying the "*difference*" had an effect on their motor strategies for the bi-manual spring pulling task. This corroborates with the relatively lower stretched spring length (l_f) for treatments **T3** and **T4** —

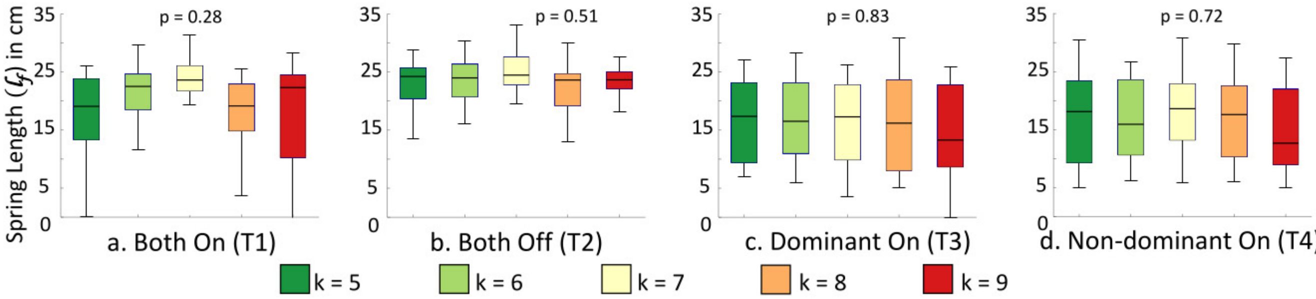

Fig. 7. Stretched spring length for symmetric bi-manual actions compared across different stiffness values for each treatment type. $p-values$ are measured from a single factor ANOVA conducted for each treatment.

selective activation/ deactivation of devices compared to conditions where the feedback was either completely on or off. Our observations suspect the early onset of asymmetric forces for a certain stiffness k might have made the "*difference*" more perceptible in the early duration of the trial (Fig. 7(c),(d)). Another participant stated about "*experiencing strain*" in either upper limbs as a cue to identify asymmetry in force-feedback. In the same spirit, one participant discussed about relying on the kinesthetic perception of their dominant hand for identifying kinesthetic perceptual asymmetry across different stiffness' and experiment controls.

7.2 Learnability

Learnability is a key attribute of any study task observed across independent trials as well as in terms of user approach towards the task. In our experiment, 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, but found it difficult to differentiate for lower magnitudes. This could be observed for the relatively longer mean stretched spring length l_f for cases where the force-feedback was active for both hands or completely deactivated which indicates the perceptual illusions of asymmetry experienced by the participants at lower stiffness values k. Out of 9 participants, only 1 claimed improved kinesthetic perception with successive trials in identifying asymmetric forces in each hand. Therefore, our experiment while being controlled, maintained a systematic randomization that kept the successive trials independent from the prior ones.

7.3 Visual Cues

Based on our pilot studies, we provided a visual guidance in the form of a physical line illustration (Fig. 1) for participants to maintain a linear pulling motion. We observed that most participants utilized the illustration as a visual aid for maintaining a near linear motion in space, as well as, it helped a few to imagine a virtual spring to relate with the resistive force-feedback experienced during the experiment. While useful, few participants expressed discomfort in using the lines as a reference as it diverted their focus from perceiving asymmetry, which also led to false positives in identifying symmetric forces on both of the upper limbs.

7.4 Video Analysis

Each user trial lasted approximately for $3-4$ seconds on an average and each study took about 30 minutes. Due to the short duration of each user trial, we analyzed the video at normal (30fps) and 0.5x (15fps) speeds to make a clearer sense of motor movements across stiffness and controls as articulated by the users' upper limbs. We identified some key motor strategies and highlights from the perspective of motoric and perceptual symmetry discussed as follows:

7.4.1 Motor Strategies

We identified three key motor strategies commonly observed across all user trials. First, almost every user started very slow in order to be more aware (or heighten their senses) to identify any asymmetric forces through bi-manual kinesthetic perception. However, for cases where both devices were either on or off, participants moved relatively faster than the selective device activation variants. In fact, we computed the average of maximum speeds for both limbs and found the *Both Devices On* condition having relatively faster bi-manual motion followed by *Both Devices Off* condition. Most participants did encounter perceptual illusions of asymmetric or symmetric forces on either limbs, especially for lower stiffness range (k = 5 N/m to 7 N/m). While aware of this, participants often found it difficult to strategize an optimal approach for kinesthetic perception. Therefore,

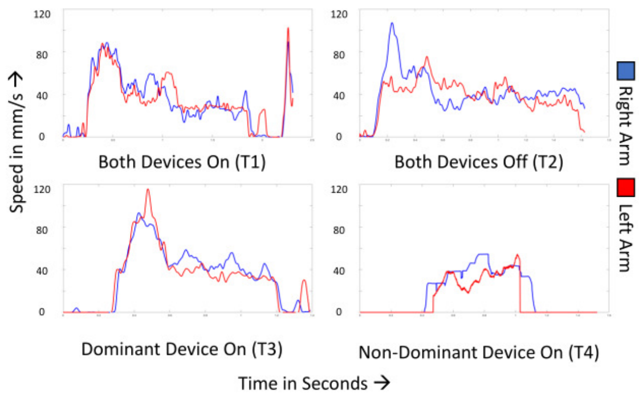

Fig. 8. Time series data representing the speed trajectories for left and right limbs for a given user trial for stiffness (k) value 6 across all 4 conditions. The curves represent near zero lag between the motion of the two upper limbs and near similar trajectory and our cross-correlation analysis confirms this synchronization. This illustration is not to drawn conclusions about user behavior but to provide a preliminary insight into the speed trends across all stiffness' and experimental controls.

the second motor strategy was to continue stretching the virtual spring than stopping at the first perceptual hint to re-confirm any asymmetry in forces . The third strategy is more of an internal *reset* mechanism where participants stretched their arms between trials to confirm the proprioceptive senses of their arms.

7.4.2 Kinesthetic Cues

Kinesthetic feedback in general was found to be prominent by the participants at higher spring lengths for lower stiffness range (k = 5 N/m to 7 N/m) and lower spring lengths for higher stiffness range (k = 8 N/m to 9 N/m). The key indicator for asymmetry in forces was the relative motion of both upper limbs i.e. as per the user-feedback, the arm with no force-feedback moved slightly faster than the one with force-feedback as the latter had a resistive force applied to that arm. For conditions where both devices were off or on, both arms moved in close synchronization as quantitatively assessed using cross-correlation analysis (Fig. 8). Irrespective of experimental controls, the participants always strived to move their arms in symmetry with respect to the shoulder joints as pivots.

7.4.3 Effect of Dominant Limb

The dominant arm is relatively more sensitive in identifying motoric as well as perceptual symmetry. While the participants intended to apply equal effort towards moving in a symmetric fashion, cases with selective activation/ deactivation of the haptic device made identification of asymmetry easier with the dominant hand i.e. asymmetry in forces was identified early (Fig. 8). However, high sensitivity in kinesthetic perception for few participants added to relatively larger false positives in identifying motion asymmetry.

Overall, the user-feedback and video-analysis furnish us with a deeper insight into the fundamental aspects of our study design, evaluation methodology, and kinesthetic perceptual symmetry from the point of varying stiffness and experiment controls. Further, the aforementioned quantitative and qualitative assessments help us investigate, evaluate, and confirm our analyses so as to draw a strong fundamental reference for future rehabilitative experiments with actual patients suffering from partial to full body motor impairment.

8 Discussion

In this paper, we study kinesthetic perceptual symmetry in bi-manual interactions from the point of quantifying kinesthetic perception in healthy individuals. At the same time we highlight few key fundamental insights on how motoric and perceptual symmetry while being independent observations are related to each other, and crucial for rehabilitative purposes. In the following sections we briefly discuss our contributions, implications, and evaluation strategies for bi-manual symmetric tasks.

8.1 Action vs. Perception

Our experiment while being simplistic, discusses few fundamental insights on kinesthetic perceptual symmetry. This perceptual attribute has been studied for decades from the perspective of physiotherapy and neurorehabilitation, however, the findings are generally subjective and lack quantitative information, making it difficult to replicate the experiments for further research. To avoid this, we use a commercially available haptic device in our work that can be programmed to provide spring-based force-feedback perceptible enough with change in spring stiffness. The kinesthetic feedback for the bi-manual symmetric spring pulling task was intended to provide spatial support, as well as, to assess how our mind and body respond to any hindrance in the symmetric forces. To this effect, we made observations that action symmetry is linked to perceptual symmetry i.e. involuntarily our minds perceive symmetry which is reflected in the "*effortless*" proprioceptive action of our upper limbs [54]. In fact, our user-feedback, video-analysis corroborate with the quantitative findings that action is controlled by perception, and any asymmetry in action is a consequence of asymmetry in perception. In addition, our primary contribution is that we identify a range of stiffness values that aligns the motor and perceptual symmetry irrespective of any experiment control by creating a kinesthetic perceptual illusion, which could be helpful for diagnosing, as well as, rehabilitation of stroke patients in future studies. While these observations are specific to our experiment, they lay the foundation for designing future study interfaces and kinesthetic bi-manual symmetric tasks with appropriate quantitative stiffness control that focus on the recovery of different levels of stroke-based motor impairments.

8.2 Joint-Space Symmetry

Kinesthetic bi-manual symmetry as discussed in existing literature have primarily focused on symmetric movements about the joint space [53, 58, 65, 68]. These works also inform our study design where the spring pulling actions are performed about the shoulder joint-space for each arm. One of the potential weakness of our study is that we explored interactions at the shoulder level, but didn't consider the joint-space symmetry (JSS) at elbow or wrist level which are articulated as well while stretching a virtual spring. In fact, this realization opens up new avenues for designing experiments for studying kinesthetic perceptual symmetry for a variety of tasks. One of the participants suggested post trials about exploring the vertical space for symmetric actions such as weight lifting or similar activities. The interesting aspect here is about adding the additional and natural effect of gravity that was absent in our horizontally defined spring pulling action, also, could be constrained at different JSS to understand the effect of individual joints on kinesthetic perception.

8.3 Evaluation Methodology

Bi-manual manipulation tasks *per se* have been extensively explored over the past few decades. In fact, there are numerous studies evaluating bi-manual actions for physiology, human-computer interaction, compliance perception, and neurorehabilitation [91–94]. As a result these works have come up with evaluation strategies that have been standardized for evaluating bi-manual spatial tasks. Due to the simplistic nature of our task, our metrics were Pearson cross-correlation coefficient and stretch length of the spring. While insightful, metrics such as Point of Subjective Equality (PSE) and Just Noticeable Difference (JND) [95] provide additional information on the motor strategy and user performance in a quantitative sense. As discussed in the aforementioned sections, our future study designs are heavily contingent upon exploring different JSS, interaction space, and evaluation methodology providing a strong quantitative and qualitative foundation for exploring kinesthetic perceptual symmetry in bi-manual actions.

9 Concluding Remarks and Future Directions

Our primary goal in this paper was to study kinesthetic perceptual symmetry in bi-manual actions from the perspective of motor and perceptual symmetry. With this goal, we introduced a novel haptics-based experimental setup and conducted an experiment 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 for a range of values of stiffness from 5 to 9, 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 few interesting insights from the point of user behavior, performance, and motor strategies. First, we observed that symmetry in bi-manual 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 higher cross-correlation coefficient (r) for speed data between the left and right hands of the user. In fact this was also observed for cases where device was on on either hands at a given time. In addition, the 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 ($k = 5$ to $k = 9$) for healthy individuals where the distance to perceptual asymmetry was observed to decrease with increasing stiffness in bi-manual 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. It would be interesting to observe if kinesthetic perception varies across different age groups such as children, adults, and old-age. 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 from the point of novel kinesthetically symmetric actions and robust evaluation methodologies. We believe that our work reveals a rich research direction that will lead to several future collaborations with medical community with real world applications in diagnostics and rehabilitation.

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