Estimating proprioceptive position sense of upper limbs using joint distance and joint angle symmetries

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Abstract

Background

Proprioceptive position sense (PPS) plays a critical role in movement and coordination of the upper limbs. It is commonly affected in neurological disorders such as unilateral spastic cerebral palsy (USCP) and stroke. However, UL PPS is often not considered during assessment or treatment in motor rehabilitation programs, in part due to limitations of current methods to quantify PPS. Traditional methods assess the similarity or symmetry of angles of a single joint and may not be sufficiently sensitive nor accurate. Emerging methods such as the use of robotic technology typically are limited to 2D and are also not standardizable as they are not easily available to clinics and research labs. This study aims to introduce a standardized and accessible way to quantify multi-joint PPS using 3D kinematic measures.

Methods

We developed novel multi-joint angle and distance-based measures of symmetry to assess upper limb PPS. Healthy adults (N = 17) and children with USCP (N=9) participated in this study. Kinematics were extracted during upper limb 3D pose matching tasks using a VICON Nexus system. Brunner-Munzel permutation tests were used for statistical comparisons between groups. Pearson's correlation coefficient was used to investigate the relationship between the different symmetry measures and pose matching tasks.

Results

We introduced novel angle and distance-based measures of symmetry to estimate PPS. Healthy adults scored higher on both these symmetry measures compared to children with USCP. Angle and distance-based symmetries did correlate with each other. Exploratory factor analysis indicated that both angle

symmetry and joint distance symmetry were highly loaded by the latent factor that best explained variance in the data. These results suggest that the two measures of pose symmetry are not redundant. It was also observed that distance symmetry was less sensitive to the different poses while angle symmetry varied across poses.

Conclusions

Symmetry measures derived from kinematics during upper limb pose matching tasks can estimate multi-joint PPS. Angle and distance-based symmetries together provide information about an individual's ability to sense joint position. This framework will allow clinicians and researchers to measure PPS of upper limbs only using kinematic acquisition devices.

Keywords

Proprioception, Position Sense, Upper Limb, Cerebral Palsy, Kinematics, Symmetry

1 Introduction

Proprioception, the ability to sense movement, position and orientation of one's body or body segments in space, is an important component of the sensorimotor system [1]. It is known to significantly be affected by brain injury disorders such as cerebral palsy (CP) and stroke [2, 3] and can affect movement and coordination [4]. Specifically position sense, an important component of proprioception that provides awareness of the position of body segments in space, is known to affect motor function [2, 5]. An increasing number of studies have linked the importance of single-joint proprioception to movement rehabilitation after injury or maldevelopment of the brain [3, 6, 7, 8]. To establish the relationship more conclusively between rehabilitation and proprioception (position sense), it is necessary to reliably measure multi-joint proprioception with sufficient accuracy. However, proprioception itself is a complex

product of the sensory and motor system and as such, cannot be directly measured but can only be approximately estimated.

Typically, proprioceptive position sense (PPS) has been estimated by looking at similarities or symmetries in joint angles during pose matching tasks. Most studies looking at position sense, have used an active or passive single-joint position matching task [9]. During passive joint matching tasks the participant is blindfolded and the target limb is gradually moved by the evaluator. The participant is asked to indicate when they think the target position has been reached. The matching can be done with the same limb or the contralateral limb. In the case of active joint-position matching tasks, if an ipsilateral matching paradigm is used, the limb is held at the target position for a few seconds and then moved back to the initial position. The participant will then be asked to replicate the demonstrated target position with the same limb without assistance from the administrator. In a contralateral matching task the participant, rather than moving the limb back to the initial position to match it with the same limb again, will be asked to hold the target limb and the target position and to match the corresponding position with the contralateral limb [10]. The experimenter or clinician will then measure the mismatch in joint angles about the limbs using a goniometer. This method comes with a few pitfalls. First, the scoring using a goniometer may be imprecise and will depend on an evaluator's training. Second, such a method usually involves the measurement of a single joint angle. The rest of the joints and limbs involved in the task are not considered resulting in an incomplete measurement of upper limb PPS.

With recent advancements in kinematics and robotics new PPS assessments such as the bimanual manipulandum [11] and the KINARM [12, 13] have been developed and adapted for children with CP [14, 15]. Most forms of PPS measurement that provide limb support are planar in nature. This limitation of 2D proprioceptive measures may also not completely capture potential loss of PPS, specifically position sense in 3D space. Furthermore, individuals with movement disorders such as CP might

experience difficulties in placing their arms onto the armrests of these devices due to fixed contractors caused by spasticity [16]. In addition, these devices have faced challenges in being adopted in clinics and research labs because of their large sizes and costs [17].

To address these concerns, based on recent literature [18, 19] we introduce a motion capture-based framework to assess multi-joint PPS of the upper limbs precisely while not providing any external arm support during contralateral pose matching tasks. We rely on the assumption that the symmetry of pose matching tasks is primarily dependent on the degree of PPS present, as previous studies have done [20, 21, 22]. We propose two ways of measuring symmetries using joint angles and relative joint distances. The measurement of joint angles for estimating PPS is already common practice. However, in 3D space, joint angles alone are not sufficient to measure symmetry since it is possible to have matching multiple joint angles, but asymmetric upper limb poses. We introduce a relative joint distance measure in our framework to address this drawback of joint angles. Here, a pose is considered symmetric if each pair of upper limb joints (elbows, wrist) are equidistant from a reference point on the body (neck, sternum etc.). We investigate both angle symmetry and distance symmetry as measures of PPS in this study.

We test these measures in a population of healthy adults who have no history of neurological disorders including proprioceptive deficits. We then apply these measures to a group of children with CP who commonly exhibit decreased proprioception. We also investigate the relationship between distance and angle-based measures of symmetry and how they are affected by the choice of task and the choice of upper limb used (in the case of children with CP).

2 Methods

2.1 Participants

Two groups of participants were tested in this study. The first group consisted of 17 healthy adults (mean age = 30.0 years; SD = 10.2; Females = 14). The second group consisted of nine children (mean age = 10.5 years.; SD = 2.8; Females = 3) diagnosed with unilateral spastic cerebral palsy (USCP). Children with USCP were recruited from a summer rehabilitation camp in 2019 that was conducted at Teachers College, Columbia University, New York City. The healthy adults recruited were interventionists, supervisors, or volunteers at the same summer rehabilitation camp in 2019. Participation was voluntary. The study was approved by the Teachers College, Columbia University Institutional Review Board. Healthy adults, children's parents/legal guardians, and the children signed a written informed consent for participation in the study.

2.2 Experimental Procedure

The participants were asked to perform active contralateral UL pose matching tasks, without any UL support, while seated. To minimize fatigue induced variability in children with USCP only one trial was performed for each pose. The first pose that was termed "superhero-powerbars" involved the participants abducting shoulders to 90 degrees with their hands in a fist pointed downwards and elbows bent at 90 degrees (see Fig 1A). The other pose, "superhero-muscles", is shown in Fig 1B. This pose is similar to the first pose except the forearms are pointed vertically upwards instead of downwards.

Participants were asked to sit on a chair comfortably but with an erect posture. For adults, the dominant upper limb was guided into a pose, and the participant was requested to mirror the pose with the other arm without looking at their upper limbs. Adult participants were requested to look straight ahead while performing the tasks to minimize effects of visual input on pose matching. For children with USCP, the upper limb was guided to a position as close as possible to the illustrated pose while minimizing

discomfort, and participants were asked to match the pose with their other arm. Children with USCP were blindfolded with sleeping masks while performing the tasks to remove any compensation arising from visual feedback. Children with USCP were tested twice for each of the two poses. First, while matching the pose with their affected hand and then while matching with their less affected hand. All participants were requested to maintain the matched poses for a period of 5 seconds. Participants were verbally cued to perform the tasks with the commands “Match”, “Hold” and “Relax” respectively.

Some participants with USCP could not perfectly assume the poses shown in Fig 1, and the pose was adjusted so the participant could achieve the pose within their comfortable active range of motion. As our primary concern was to measure contralateral symmetry of the poses we included these participants in our analyses.

2.3 Kinematic measures of PPS

To evaluate the poses and the degree of asymmetries, we used a 10-camera 3D motion capture system (VICON Nexus v 2.2.1, Lake Forest, CA) to capture kinematic data. Fourteen reflective markers were placed on the following anatomical landmarks: the neck, mid-sternum, shoulders (acromion), midarms, medial and lateral epicondyles of the elbow, mid-forearms, and the radial styloid process of the wrists. Kinematic data was captured at a sampling rate of 100 Hz. Kinematic data from the VICON Nexus (v 2.2.1) software was saved as a csv file. Data was analyzed using a Butterworth 5th order low-pass filter using a 6Hz cutoff frequency. Occasional missing data points were filled using cubic spline interpolation. For the analysis of kinematic joint data, elbow positions were calculated as the average position of the lateral and medial epicondyles.

Our proposed methodology estimated PPS by measuring symmetry of upper limb joint angles and symmetry of upper limb relative joint distances. Traditionally, joint angle symmetries have been used as a measure of PPS, however as we are now estimating PPS in 3D space, symmetry of angles alone did not

necessarily guarantee that the overall pose is symmetric. For this reason, we introduced an additional measure of symmetry using joint distances.

The distance symmetry measured the similarity of distances between corresponding left and right upper limb joints relative to a common reference point such as the neck or sternum. The distance symmetry and angle symmetry measures were estimated for every time point of the kinematic data capture while a participant was holding the pose. To further eliminate transient movements that may affect estimation of PPS, we discarded the first two seconds of data and last second of data, out of about a total duration of 5s, before analysis. The mean distance and angle symmetries were then calculated across time.

In addition to the primary symmetry measures, we also assessed how much the pose drifted while participants attempted to maintain the poses. This measure serves as an estimate of how stationary a participant was while trying to match the pose. The underlying assumption was that pose drift may serve as an indirect measure of musculoskeletal factors, since factors such fatigue and muscle tone may affect how static the pose is during the joint matching task

2.3.1 Distance Symmetry

The distance symmetry measure focused on relative positioning and distances of upper limb joints from reference points. Measurements were made from the left and right corresponding wrists or elbows to a pair of common references such as the neck and mid-sternum as seen in Fig 2A and Fig 2B respectively. For each reference two pairs of measurements are made. With the neck as a reference, the first pair of measurements were the distances of the right wrist to the neck (r_{RWN}) and the left wrist to the neck (r_{LWN}). The second pair of measurements were the distances of the right elbow to the neck (r_{REN}) and the left elbow to the neck (r_{LEN}) as shown in Fig 2A. With the mid-sternum as a reference, the first pair of measurements were the distances of the right wrist to the mid-sternum (r_{RWS}) and the left wrist to the

mid-sternum (r_{LWS}). The second pair of measurements were the distances of the right elbow to mid-sternum (r_{RES}) and the left elbow to the mid-sternum (r_{LES}). For each reference, the ratio of the absolute difference in distance of joints within a pair was computed as shown in the equations below. Then the maximum distance ratio between the two pairs of joints were subtracted from unity to get the distance symmetry measure. The distance symmetry measure was computed using both neck and mid-sternum references and the lowest value was considered. The distance symmetries were effectively scaled such that 1 indicated perfect symmetry in terms of distance of joints from the reference points while values close to 0 indicated that the symmetry of distances is low.

$$r_1 = 1 - \left(\frac{|r_{RWN} - r_{LWN}|}{(r_{RWN}, r_{LWN})}, \frac{|r_{REN} - r_{LEN}|}{(r_{REN}, r_{LEN})} \right)$$

$$r_2 = 1 - \left(\frac{|r_{RWS} - r_{LWS}|}{(r_{RWS}, r_{LWS})}, \frac{|r_{RES} - r_{LES}|}{(r_{RES}, r_{LES})} \right)$$

$$S_P = r_x$$

Here r_1 and r_2 represent the distance symmetries using the neck and mid-sternum as reference points, respectively. For example, if the neck is used as a reference point and the pose is perfectly symmetric then r_1 becomes 1. This is because the distances from the right wrist to the neck and the left wrist to the neck are the same as are the distances from the right elbow to the neck and left elbow to the neck. The overall distance symmetry measure S_p is the minimum of $[r_1, r_2]$. We use the minimum instead of the mean because the lesser of the two distance symmetries is more representative of differences between the left and right sides of the upper limb poses.

2.3.2 Angle Symmetry

This measure compared the similarity of the angles of the pose between the left and right upper limbs. Angle Symmetry was based on the measurements of the angles subtended about the shoulder and

elbow joints of the upper limbs. The pairs of angles measured are illustrated in Fig 3. The angles were calculated from the 3D vectors representing the following segments: wrist-elbow, elbow-shoulder, and left shoulder – right shoulder. These vectors in turn were directly calculated from the kinematic data obtained from the VICON system. For each pair of angles, we first found the ratio of differences of the angles to the larger value of the two angles. The symmetry was then obtained by subtracting this ratio from 1. This scaling causes the symmetry metric to range between 0 and 1, where 1 indicates a perfect match of the angles on the left and right side while a value close to 0 indicates a very large mismatch between angles. To calculate the overall angle asymmetry S_A , we used the following equations:

$$S_A = 1 - \left(\frac{|\theta_{RELB} - \theta_{LELB}|}{(\theta_{RELB}, \theta_{LELB})}, \frac{|\theta_{RSHLD} - \theta_{LSHLD}|}{(\theta_{RSHLD}, \theta_{LSHLD})} \right)$$

Here, θ_{RELB} and θ_{LELB} represent the pair of angles subtended by the right and left elbows, respectively. θ_{RSHLD} and θ_{LSHLD} represent the pair of angles subtended by the right and left shoulders, respectively. The overall angle symmetry measure S_A is obtained by considering the lowest symmetry value of the elbow and shoulder angle symmetries. We take the minimum angle symmetry instead of the mean because the lower symmetry measure best captures the asymmetry of a pose.

2.3.3 Pose drift

Pose drift was estimated as the total distance moved in centimeters, by the wrist joints in space during the hold period of the poses. It was assumed that pose drift would be indicative of both proprioception [23] as well as other musculoskeletal factors such as fatigue, differences in muscle tone and muscle weakness. Therefore, measuring pose drift during the “hold” period of the matching task might provide information on whether musculoskeletal factors are present and if they affect pose symmetry.

The wrists alone were used to calculate drift because any movement in the shoulders, elbows, or trunk would be reflected as a movement of the wrists. Therefore, it was sufficient to capture the drift over

time of the wrists alone. Additionally, the pose drift was taken as the largest distance travelled by either the left or right wrist joints since this measurement is meant to represent the stillness of the participant while maintaining static poses.

2.4 Statistical Analysis

To compare groups of data, we used the two-sided Brunner-Munzel statistic in a permutation test [24]. This test is most suitable for non-parametric data with small sample sizes. We used 10,000 permutations for each test to obtain a statistical distribution using the Brunner-Munzel statistic. This distribution as well as the observed Brunner-Munzel statistic on the original data was used to compute the P value using an alpha of 0.05. Multiple comparisons were addressed using the Bonferroni Post-hoc correction.

To observe the possibility of a linear relationship between measures or groups, we used the Pearson's correlation coefficient (PCC). To find out if the direction and value of the Pearson's correlation coefficients were truly representative of a relationship and not due to chance, we also performed a permutation test using PCC as a statistic. For each comparison, the values within the two lists of measurements were permuted randomly for 10,000 times. A corresponding PCC was obtained for each permutation. These PCC values were then used to construct the correlation distribution against which the original PCC value was tested for significance using an alpha of 0.05. Principal component Analysis (PCA) and Exploratory factor analysis (EFA) was performed to assess the relative loadings on angle and distance symmetries by proprioception as an assumed latent factor.

2.5 Software Methods

All the measures and statistical analyses described previously were implemented using python 3.7. Data loading and preprocessing was done with the Pandas package. Statistical testing and signal processing were done using the SCIPY package while PCA was done with the Scikit-learn package. All figures in this paper were created with the Matplotlib and Seaborn packages.

The final codes for extracting the various measures and statistically examining them are available as a toolkit in a repository [25]. This repository also includes the raw data acquired from VICON and all the code created for generating results in this paper.

3 Results

3.1 Symmetry measures of PPS in healthy adults

In Fig 4A and 4B, we present the symmetry measures for the superhero-powerbars and superhero-muscles. As expected, the healthy adults demonstrated high scores on both measures of symmetry (close to 1). In the superhero-powerbars pose we observed that the mean distance symmetry of healthy adults was 0.93 ± 0.03 . The mean angle symmetry of this group was 0.94 ± 0.03 . We also found that the mean pose drift was 3 ± 1 cm. For the superhero-muscles pose, the mean distance symmetry was 0.94 ± 0.03 . The mean angle symmetry was 0.93 ± 0.03 and the mean drift was 2 ± 1 cm.

To understand the effects of the pose type on the symmetry measurements as well as to discern the relationship between the different measures, we calculated the correlation between poses and corresponding measures using Pearson's correlation. The results are presented as a correlation matrix in Fig 4C. We see that the distance symmetry measures for superhero-powerbars and superhero-muscles are moderately-to-strongly correlated ($r = 0.67$, $P = 0.008$), however the angle symmetries for the two poses are poorly correlated ($r = -0.1$). We also observed that distance and angle symmetries are only weakly correlated across the superhero-powerbars and superhero-muscles poses ($r = 0.38$ and $r = 0.33$ respectively, $P > 0.1$).

The pose drifts across the two poses are moderately correlated with an $r = 0.46$ ($P = 0.06$). Distance symmetry and pose drifts saw a moderate-to-weak correlation within both superhero-powerbars ($r = -0.47$, $P = 0.06$) and superhero-muscles ($r = -0.24$, $P > 0.1$) respectively. Similarly, correlations between

angle symmetry and pose drift within the tasks, superhero-powerbars and superhero-muscles, were found to be $r = -0.49$ ($P = 0.04$) and $r = -0.22$ ($P > 0.1$) respectively. This suggests that drift in the pose may contribute to asymmetries in the pose matching task for healthy adults. The negative correlations indicate that pose symmetries increase with less drift (subject is more stationary).

3.2 Symmetry measures of PPS in children with unilateral spastic cerebral palsy matching with their affected hand

For children with USCP using their affected hand for contralateral joint matching, the symmetry and drift measurements of the superhero-powerbars and superhero-muscles poses are shown in Fig 5A and 5B, respectively. We observed that the mean distance symmetry for the superhero-powerbars pose was 0.83 ± 0.06 while the mean angle symmetry was measured to be 0.81 ± 0.12 . The mean pose drift was 9 ± 5 cm. In the case of the superhero-muscles pose, the mean distance symmetry was measured as 0.80 ± 0.10 and the mean angle symmetry was 0.77 ± 0.15 . The corresponding mean drift for the pose was found to be 9 ± 5 cm. We observed that children with USCP generally had much more interindividual variability in scores that tended to be noticeably lower than healthy adults. Lower symmetry scores were expected in this group because USCP is known to affect proprioception [3]. The group also exhibited increased pose drift while trying to maintain their static pose during the task. This may be due to a combination of reasons such as decreased proprioception, fatigue, differences in strength, muscle tone, and range of motion.

We again investigated the relationships between measures and across the two different poses. We show the correlation matrix in Fig 5C. We find that the distance symmetries across the superhero-muscles and superhero-powerbars poses are relatively well correlated with an $r = 0.68$ ($P = 0.09$). We also find that in children with USCP, distance and angle symmetries are moderate-to-strongly correlated within each pose type. For superhero-powerbars, the distance-angle symmetry correlation is $r = 0.76$ ($P = 0.036$) and

for superhero-muscles the distance-angle symmetry correlation is $r = 0.54$ ($P = 0.17$). However, the correlation between angle symmetries across the two joint matching tasks remains low ($r=0.33$, $P=0.41$) as was in the case of healthy adults. In children with USCP, we found that the pose drifts were uncorrelated across the poses ($r = 0.02$). Pose drift was also uncorrelated with distance symmetry in the superhero-powerbars pose ($r = 0.04$, $P > 0.1$) as well as the superhero-muscles pose ($r = 0.17$, $P > 0.1$). The pose drifts were only weakly correlated with angle symmetries for the superhero-powerbars and superhero-muscles poses with $r = 0.15$ and $r = 0.08$ respectively. These distance-angle symmetry correlations significantly differ from healthy adults. The difference in correlations between measures and between the two groups also indicates that distance and angle symmetries are **not** measuring the same aspects of PPS. We explore this further in the next section.

3.3 Distance and angle symmetries as indicators of PPS

As noted in sections 3.1 and 3.2, we observed that distance symmetry and angle symmetry were not always correlated. We inferred that the two measures were both capturing some aspects of decreased PPS. To investigate this assumption, we pooled symmetry measures of healthy adults and children with USCP for each of the two joint matching poses. Figures 6A and B shows the scatter plots of the pooled data. Distance symmetry and angle symmetry can differentiate the two groups with an intercluster distance of 0.14 ($P < 0.001$) and 0.16 ($P < 0.001$) for the superhero-powerbars and superhero-muscles poses, respectively. When we look within each group across the two poses (Figs 6C and D), we conversely find that the separation of clusters based on distance and angle symmetries are much weaker, with an intercluster distance of 0.01 ($P > 0.1$) and 0.04 ($P > 0.1$) for the Superhero powerbars and muscles poses, respectively.

These results tell us two things. Firstly, that the symmetry measures can reliably distinguish between populations of healthy adults and children with USCP. Also, on the surface, each group performs

similarly across the two poses in terms of distance and angle symmetry. However, the question remains as to how angle and distance symmetries are related to PPS and how do they explain the data we observe. We address this question by performing EFA.

The underlying assumption in this work is that symmetries of the upper limbs are indicators of the degree of proprioception present. To verify if this assumption is true, we performed EFA on our data for each pose separately. Data from both healthy adults and children with USCP were combined for the analyses. Performing PCA provided us with 3 orthogonal components that explained the variance in the data. We chose to select two components in our factor analysis since they explained more than 90% of the data's variance. We then performed a factor analysis with VARIMAX rotation on the data to identify factor loadings. The resulting analysis is represented in Fig 7.

We found that the first component was strongly loaded (absolute value) by both angle and distance symmetries (> 0.8) while not loaded by the drift measure as much (< 0.5). This was found to be true for both superhero-powerbars and superhero-muscles poses (see Figs 7A and B). This component was also found to explain about 70% of the data overall. Another observation is that the direction of loading of this component on pose symmetries and drift were in opposite directions. The strong loading of this component on pose symmetries as well as the directionality of the loading suggests that this component may represent loss of proprioception as a latent factor.

The second component that explained data variance only very weakly loaded (absolute value) on to any of the symmetry measures (< 0.3). However, the drift was moderately loaded by this component in superhero-powerbars (0.66) and weakly loaded by this component in super-hero muscles. This component explained about 20% of variance in the data. The fact that this component loaded much more onto drift than symmetries suggests that it may be a latent factor that explains how stationary participants were during the tasks rather than it being a latent factor related to proprioception.

3.4 Comparing symmetry measures between the more affected and less affected hand of children with unilateral spastic cerebral palsy

Children with USCP performed the joint matching tasks using their more affected hand as well as their less affected hand. In the case of matching poses with their less affected hand (see Fig 8), we found children with USCP to have a mean distance symmetry of 0.82 ± 0.09 , a mean angle symmetry of 0.82 ± 0.07 , and a mean pose drift of 9 ± 7 cm for the superhero-powerbars pose. In the case of the superhero-muscles pose, we found that this group had a mean distance symmetry of 0.78 ± 0.05 , mean angle symmetry of 0.78 ± 0.13 and a mean pose drift of 9 ± 4 cm.

A systematic comparison of the symmetry measures and pose drift for affected hand (AH) vs. less affected hand (LAH) shows no significant differences (Table 1). This result can be understood by considering the role of PPS on the task itself. In the case of matching performed with the less affected hand, decreased PPS in the affected upper limb leads to the participant being unaware of the limb pose to be matched. In the case of matching with the affected hand, the participant may be aware of what the target pose is but is unable to accurately position the matching limb due to decreased PPS. In both cases if PPS in one arm is reduced, there will be asymmetries in the resulting poses. This could possibly lead to similar measures of distance and angle symmetries regardless of using AH or LAH for the pose matching tasks (see Table 1).

USCP AH vs LAH	Distance Symmetry	Angle Symmetry	Pose Drift
Powerbars pose	AH: 0.83 ± 0.06 LAH: 0.82 ± 0.09 p value: 0.66	AH: 0.81 ± 0.12 LAH: 0.82 ± 0.07 p value: 0.80	AH: 9 ± 5 cm LAH: 9 ± 7 cm p value: 0.85
Muscles pose	AH: 0.80 ± 0.10 LAH: 0.78 ± 0.05 p value: 0.29	AH: 0.77 ± 0.15 LAH: 0.78 ± 0.13 p value: 0.96	AH: 9 ± 5 cm LAH: 9 ± 4 cm p value: 0.89

Table 1: Comparison of distance symmetry, angle symmetry and pose drift measures between affected hand (AH) and less affected hand (LA) of children with USCP performing the superhero-powerbars and muscles joint matching tasks. There were no significant differences observed in any of the comparisons.

4 Discussion

The objective of this study was to develop a framework to measure PPS of the upper limbs quantitatively and reliably across multiple joints in 3D space. We used joint distance symmetry and joint angle symmetry as the primary measures of PPS. These symmetry measures were developed based on the assumption that pose symmetries are representative of position sense. This assumption is still used in both traditional and newer robotics-based measures of PPS for single joints [9, 15]. We then tested the framework using kinematics acquired from the VICON, as a proof of concept, in groups of healthy adults and children with CP. We also made this framework easily accessible as a toolkit for other researchers and clinicians to use.

In healthy adults in whom proprioception was expected to be intact, we observed that the symmetry measures were close to 1 (perfect symmetry). Adults had relatively low variability in their measures and low pose drift (2-3 cm of wrist movement over 2 seconds). We found that distance symmetry correlated well across both pose matching tasks for adults ($r = 0.67$). However, angle symmetries did not show strong correlation across the tasks ($r = -0.1$). Angle symmetries also did not correlate well with distance symmetry within each task ($r < 0.4$). In healthy adults, we saw that pose drift moderately correlated with itself across the two pose matching tasks ($r = 0.46$). There were also weak-to-moderate correlations between pose drift and distance symmetry for the superhero-powerbars ($r = -0.47$) and superhero-muscles ($r = -0.24$) poses. We also saw similar patterns of correlations between pose drift and angle symmetry for the superhero-powerbars ($r = -0.49$) and superhero-muscles ($r = -0.22$) poses.

In children with USCP, in whom proprioception was believed to be compromised to varying degrees [3, 14], we observed significantly lower scores (14 to 17 percent lower than healthy adults, $P < 0.05$ for all cases) for distance and angle symmetries. Children with USCP also exhibited up to five times greater variability in their measures compared to healthy adults. They also exhibited significantly more pose

drift (about 9 cm of total wrist movement over 2 seconds) while trying to maintain their static poses. As in the case with the healthy adults, we found that distance symmetries correlated well across the pose matching tasks ($r=0.68$). Additionally, we again observed that angle symmetries did not correlate strongly across the two pose matching tasks ($r=0.33$). However, unlike healthy adults, we observed in children with USCP that distance and angle symmetries were better correlated for both the superhero-powerbars ($r=0.76$) and the superhero-muscles ($r=0.54$) poses. A possible explanation for this difference between the two groups is that children with USCP cover a broader range of values in both distance and angle symmetries while the measures for healthy adults are more tightly and circularly distributed (see Figs 7A and B), leading to weaker correlations. Another observed difference was that in children with USCP, pose drifts only weakly correlated with distance and angle symmetries. ***The lack of correlation of pose drift with distance and angle symmetries in children with USCP, indicates that drift due to potential musculoskeletal factors in a neurological population do not largely contribute to differences in distance and angle symmetries in this population of children with USCP.***

A common finding in both healthy adults and in children with USCP was that distance symmetries correlated well across different post matching tasks while angle symmetries did not. This implies that the measured angle symmetries, but not distance symmetries, are affected by the type of pose matching tasks as noted in previous studies [26]. Therefore, it may be important to consider multiple poses when using this measure. These findings also suggest that distance and angle symmetries were not redundant and measured different aspects of the pose. ***This implies that PPS as measured by upper limb symmetry in 3D space during the joint matching tasks requires a multifaceted approach using both angle and distance symmetry.***

In the framework proposed, the measures used to estimate PPS were distance and angle symmetries. As such, the assumption made was that proprioception was a latent factor that strongly affects symmetry measures. Using EFA (See Fig 7A and B), we observe that regardless of the pose matching task, the first

414 component that explains about 70% of the data, strongly loads on to distance and angle symmetry
415 measures. It, however, does not significantly load on to drift. This observation leads us to interpret that
416 the first component is primarily representative of PPS. This suggests that distance and angle symmetries
417 are more representative of PPS compared to pose drift. Also considering that pose drift was primarily
418 assumed to be indicative of musculoskeletal factors and the fact that the second component primarily
419 loads on to pose drift and only weakly on to the symmetry measures, leads us to hypothesize that the
420 second component may indeed be indicative of musculoskeletal factors rather than PPS. More data and
421 information on muscle tone needs to be collected to support this finding. The findings of this study
422 suggest that measured angle and distance symmetries of joint matching tasks are indicative of the
423 degree of PPS present in individuals with and without neurological disorders.

424 We also investigated if the measures obtained from the pose matching tasks varied depending on which
425 UL was used for matching in children with USCP. We compared the measures from joint matching tasks
426 where children with USCP first used their affected hand to perform the matching, followed by using
427 their less affected hand to perform the matching task. Interestingly, the results showed no significant
428 differences in the measured angle or distance symmetries or pose drifts between matching with the
429 affected or less affected limb. ***These results suggest that performance of the pose matching task was***
430 ***not affected by which upper limb was used to perform the active matching.*** Impaired PPS in the target
431 limb may result in an indistinct internal representation of the limb, making it difficult to match with the
432 test limb even if that limb retains sufficient PPS. Conversely, impaired PPS in the matching limb would
433 limit accuracy even if an appropriate internal representation was formed of the reference limb as they
434 would not have sufficient PPS acuity to match that. Similar observations have also been reported in
435 other studies of USCP [6] as well as other disorders where proprioception has been affected [27].
436 Another possible explanation for the similar symmetry measures observed, regardless of which UL limb
437 was used by children with USCP, is that bimanual activities are regulated through the corpus callosum. It

is the primary structure that integrates activity across both hemispheres. Using diffusion magnetic resonance imaging, a recent study showed that children with USCP have structural abnormalities of the corpus callosum in addition to having high structural variability between children with USCP [28]. Considering that white matter integrity of the corpus callosum may be critical for bimanual pose representation (such as the superhero-powerbars and superhero-muscles poses), this may also explain why PPS may seem equally impaired regardless of matching with the AH or LAH in children with USCP.

4.1 Limitations

There are a few limitations in this study that will need to be addressed in future work. Firstly, the two groups of participants used in this study to demonstrate the measures were not age matched. The goal of this study was not to compare and explain proprioceptive differences between healthy adults and children with USCP. Rather, we used the fact that children with USCP generally exhibit deficits in proprioception to demonstrate that our proposed measures were sufficient to detect those deficits. Furthermore, in children with USCP aged between 8 to 16, age and pose symmetries correlated very weakly ($r < 0.3$), indicating that age was not a factor in these measurements.

Secondly, the group of children with USCP had a relatively small sample size of 9. This small sample size could skew some of the analyses, especially correlations, which are sensitive to sample sizes. To further address this limitation our next steps would be to do an age-matched study with a larger sample size to understand PPS differences between children with USCP and typically developing children. Based on our findings in this paper, a power analysis for correlation ($\alpha = 0.05$, power = 0.8, $r = 0.5$) indicated that we would need at least 29 children in each group to obtain more reliable correlation coefficients between our proposed measures.

Another limitation is that these matching tasks do not provide arm support. No support of the upper limbs during the task would mean that individuals with severe motor impairments and/or poor muscle

tone may not be suitable for PPS evaluation using our measures. EFA performed in this study strongly indicates that the pose drift (which is assumed to also be representative of musculoskeletal factors) is not highly loaded by the same component that strongly loads onto the pose symmetries. This possibly suggests that pose drift, and by extension musculoskeletal impairments, may not have a strong impact on pose symmetries. Another more pragmatic approach (for individuals without severe motor deficits) may be to first collect a baseline assessment of distance and angle symmetries where individuals can use visual perception to perform the joint matching tasks. In this way, any baseline asymmetries in pose or joint angles can be largely attributed to non-proprioception-based factors. The same individuals can then be blindfolded and asked to perform the joint matching tasks again. Any difference between the distance and angle symmetries in this case when compared to the baseline, may more likely be due to proprioception-based deficits.

5 Conclusion

We identified a set of measurements to assess PPS using kinematic data captured during unassisted joint matching tasks in 3D space. We demonstrated how these measures could detect differences between healthy adults and children with USCP. We also demonstrated that the angle and distance symmetry measures are not redundant. We provide these measures that can be extracted from kinematic data as a Python toolkit. These measures and the toolkit are not tied to any one specific system and can easily be extended for use in any kinematics-based system. The most salient features of the proposed measures in this study are that they are quantitative, continuous (can theoretically measure position sense across time), and exhibit both robustness across trials/poses and sensitivity to PPS. Additionally, assessment of PPS for a single trial using this approach takes less than 10 seconds. This implies that research involving the investigation of rehabilitation and proprioception can be easily and

483 frequently be carried out with portable and affordable kinematic acquisition equipment [29] using this
484 measurement tool.

485 6 List of abbreviations

486 PPS – Proprioceptive Position Sense
487 USCP – Unilateral Spastic Cerebral Palsy
488 UL – Upper Limb
489 PCA – Principal Component Analysis
490 EFA – Exploratory Factor Analysis

491 7 Declarations

492 Ethics approval and consent to participate

493 The study was approved by the Teachers College, Columbia University Institutional Review Board.
494 Healthy adults, children’s parents/legal guardians, and the children signed a written informed consent
495 for participation in the study.

496 Consent for publication

497 Not applicable.

498 Availability of data and materials

499 All deidentified motion capture data and analysis code is available at our PEACK Github repository:
500 <https://github.com/shivak7/PEACK/tree/master/Proprioceptive%20Position%20Sense>

501 Competing interests

502 The authors declare that they have no competing interests.

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508 Authors' contributions

509 SRG developed and implemented the symmetry measures for measuring proprioceptive position sense,
510 analyzed the kinematics data, and drafted the manuscript. MTR and DD collected and processed
511 participant data to extract kinematics and were major contributors to writing the manuscript. TK, AMG
512 and KMF provided expert advice and valuable feedback with substantial contributions to the drafting of
513 the manuscript. All authors were involved in the design of the study.

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9 Figure Legends

Figure 1: Poses used for estimating proprioception. **A)** Superhero-powerbars: Lower arms point vertically downwards. A ninety-degree angle is subtended around the elbows. Elbows are collinear causing a 180-degree angle to be subtended around the shoulders as shown. **B)** Superhero-muscles: Similar to superhero-powerbars but with forearms pointing vertically upwards.

Figure 2: Distance symmetry measure. **A)** Ratios of distances of right wrist to neck (rRWN) and left wrist to neck (rLWN) are measured. Similarly, the ratios of distances of right elbow to neck (rREN) and left elbow to neck (rLEN) are measured. The ratios are closer to 1 the more symmetric the pose matching is. **B)** Again, we measure the ratio of distances of the wrist and elbow joints to a reference position which is the mid-sternum instead of the neck.

Figure 3: Angle symmetry of upper limb joints based on the angles subtended by the right and left elbows as well as the right and left shoulders. The ratios of corresponding angles are used to compute angle symmetry. The closer the ratios are to 1, the more symmetric the pose.

Figure 4: Symmetry measures of healthy adults. **A)** For the superhero-powerbars pose, distance symmetry was 0.93 ± 0.03 , angle symmetry was 0.94 ± 0.03 and pose drift was 3 ± 1 cm. **B)** For the superhero-muscles pose, distance symmetry was 0.94 ± 0.03 , angle symmetry was 0.93 ± 0.03 , and pose drift was 2 ± 1 cm. **C)** Correlation matrix comparing measures and poses. Darker colors indicate higher correlation. Distance symmetries are well correlated across the two joint matching tasks while angle symmetries are not.

Figure 5: Symmetry measures of children with USCP. **A)** For the superhero-powerbars pose, distance symmetry was 0.83 ± 0.06 , angle symmetry was 0.81 ± 0.12 and pose drift was 0.09 ± 0.05 m. **B)** For the

611 superhero-muscles pose, distance symmetry was 0.8 ± 0.1 , angle symmetry was 0.77 ± 0.15 , and pose
612 drift was 0.1 ± 0.05 m. **C)** Correlation matrix comparing measures and poses: Darker colors indicate
613 higher correlation. Distance symmetries are well correlated across the two joint matching tasks while
614 angle symmetries are not. Within the same task, we also find that distance-angle symmetries are better
615 correlated for children with USCP.

616 **Figure 6: A-B)** The two groups. Healthy adults and children with USCP, show significant separation in the
617 metric space defined by distance and angle symmetry. The healthy adult scores are generally tightly
618 clustered in the upper right quadrant, indicative of overall high symmetries. There is a relatively large
619 intercluster distance (distance between centroids) between the two groups. **C-D)** Within each group we
620 see there is no significant separation of the symmetry measures based on the type of joint matching
621 task.

622 **Figure 7:** Factor loadings on the first two components that explain > 90% of variance for A) superhero-
623 powerbars and B) superhero-muscles. In both cases the first component primarily loads strongly onto
624 the pose symmetries while the second component loads more on to pose drift.

625 **Figure 8:** Symmetry and pose drift measures from children with USCP performing the joint masking tasks
626 using their less affected hand. The measures do not differ much regardless of the choice of hand used to
627 perform the joint matching tasks.