Original Research

Testing Precision and Accuracy of an Upper Extremity Proprioceptive Targeting Task Assessment

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Abstract *Objective:* To develop and test an assessment measuring extended physiological proprioception (EPP). EPP is a learned skill that allows one to extend proprioception to an external tool, which is important for controlling prosthetic devices. The current study examines the ability of this assessment to measure EPP in a nonamputee population for translation into the affected population.
Design: Measuring precision and accuracy of an upper extremity (UE) proprioceptive targeting task assessment. Participants completed 2 sessions of a targeting task while seated at a table. The targeting was completed with the dominant and nondominant hand and with eyes open and eyes closed during the task. Participants completed 2 sessions of the clinical test with a 1-week washout period to simulate reasonable time between clinical visits.
Setting: Research laboratory.
Participants: Twenty right-handed participants (N=20) with no neurologic or orthopedic deficits that would interfere with proprioception, median age of 25 years (range, 19-33 years), completed the assessment (10 men, 10 women).
Interventions: Not applicable.

Main Outcome Measures: Precision (consistency in targeting) and accuracy (distance between the intended target and participant result) in UE targeting task using EPP; test-retest repeatability between sessions.

Results: Both precision and accuracy were significantly decreased in the eyes-closed condition compared with the eyes-open condition regardless of targeting with dominant or nondominant hand (all $P<.001$). In the eyes-open condition, there was a dominance effect relating to the accuracy; however, in the eyes-closed condition, accuracy between dominant and nondominant hands was statistically equivalent. Based on minimum detectable change with 95% confidence, there was no change in either metric between the first and second sessions.

Conclusions: The results of this study support the feasibility of using this assessment to measure EPP—based on the definition of EPP as a learned skill that indicates control over an external, simple tool—because they demonstrate reliance on proprioception in the eyes-closed condition, symmetry in proprioceptive accuracy between hands for within-participant control, and test-retest reliability for longitudinal measurements. The results also establish normative values for this assessment in young, healthy adults. Further research is required in a clinical population to evaluate the UE proprioceptive targeting task assessment further and collect objective data on EPP.

Perception of a limb's movement or location through space is termed proprioception and arises from sensory neurons in the muscles, tendons, and skin.[1] Proprioception is a standard clinical measurement for assessing limb function and control in cases such as orthopedic rehabilitation, stroke recovery, and Parkinson disease progression.[1] When individuals have diminished proprioception, their dependence on visual information increases.[2] Conversely, when the visual field is limited, the individual relies on proprioception more heavily for accurate movement.[3] Proprioception can be extended beyond the body, through extended physiological proprioception (EPP). EPP is a learned skill that allows one to extend proprioception outside the body to control a simple tool, such as a prosthetic device.[4] Effective EPP requires a 1-to-1 relationship between the positioning of the body and of the connected tool.[4]

We have anecdotal support for improved EPP when using a percutaneous osseointegrated (OI) endoprosthesis from individuals with transfemoral amputation.[5] These individuals with transfemoral OI endoprostheses provided subjective feedback of perceived improvements to accuracy and control over foot placement during functional activities compared with their experience using a conventional socket. Percutaneous OI endoprostheses are an alternative prosthesis suspension system to the conventional socket suspension system. OI endoprostheses eliminate the need for a socket by directly connecting the prosthetic device to the residual bone. In the upper extremity (UE), OI is expected to reduce socket interface-related weight and pain, improve shoulder range of motion, and potentially increase control of the prosthetic device through the elimination of movement between the socket and the residual limb because of skin elasticity, muscle contraction, and inertia of the prosthesis.[6]

Individuals with transhumeral (TH) amputations have the highest rate of prosthesis abandonment, up to 60%,[7-9] with women typically less likely to wear a prosthesis than men.[10] Abandonment (self-reporting no longer using a prosthetic device) or limited use (<8 hours on workdays and <5 hours on days off)[11,12] of a prosthesis prevents an individual with TH amputation from completing many bilateral activities of daily living. Common reasons for abandonment include the weight of the device, pain from socket pressure, decreased range of shoulder motion, and an inability to control the device.[8,13]

Although we did not attempt to measure changes to EPP in the cohort of individuals who received transfemoral OI endoprostheses, we expect that their experience with improved accuracy and control over the prosthetic device will be experienced by individuals who receive a TH OI endoprosthesis as well. This improvement is critical given the complexity of UE movement during activities of daily living and the effect an individual's control over the prosthetic has on their use of and the likelihood of abandoning the device. As we continue work with OI in individuals with TH limb loss, it will be important to measure changes in EPP.

However, conventional methods of measuring proprioception assess it at individual joints rather than the entire limb[14,15] and therefore cannot measure EPP. To address this gap, we developed a UE targeting task assessment to measure EPP via a participant's ability to target a point in space using a simple tool connected to their UE. While the motivation for this UE targeting task assessment stems from our work with UE amputees, the successful development of this tool will enable measurement of EPP in a wide range of fields where multijoint proprioception is of interest. The current study was completed in nonamputee individuals.

Because EPP is augmented by visual input and a learned skill, we hypothesized that if this targeting task was measuring EPP, (1) the UE proprioceptive targeting task will be sensitive enough to distinguish eyes open and eyes closed conditions and (2) completing the targeting task with the dominant hand will result in better accuracy compared with completing the targeting task with the nondominant hand. Additional objectives of this study were to examine test-retest reliability, through repeated measures, and feasibility of clinical adaptation, through investigating how to minimize the time to complete the assessment.

Methods

Participant recruitment

We recruited 20 right-handed nonamputee adult participants to participate in this study. Data for active repositioning based on proprioception[16] was used to estimate sample size through a paired t test power analysis (α=0.05, power=0.8) and a 2 one-sided tests (TOST) power analysis (α=0.05, power=0.8), finding that a sample size of 20 would be able to detect an effect size of 0.14 with equivalence bounds of $\pm$0.5 cm. All procedures were approved by the local Institutional Review Board, and all participants provided written informed consent. Participants 18 years and older were recruited. To avoid diminished proprioception associated with advanced age, recruitment was targeted at young adults and did not include individuals older than 60 years.[17,18] Exclusion criteria included decreased mobility of the UE or any condition known to the participant that could affect proprioception (eg, neuromuscular impairment, orthopedic impairment, connective tissue disease, limited vision, etc).[19] If the participant verbalized any condition that was unclear if it would affect proprioception, a clinician was consulted, and if appropriate the participant was not included in the study.

Test protocol

Participants sat at a table, with elbows shoulder-width apart on the edge of the table and forearms straight out resting on the table (fig 1). The participant held a marker (simple tool) in each hand using a self-selected grip. The researcher placed a test paper in front of the participant. This paper was in landscape orientation with an X in the middle of the page as a standardized target. The target was aligned to the sagittal plane of the participant, and the near edge of the paper was aligned with the participant's metacarpophalangeal joint, requiring mediolateral and anteroposterior movement to reach the target.[20]

Procedures

To limit each session to 30 minutes, sessions were composed of 40 trials broken into 4 equal instructional blocks of 10 trials: block 1: left hand/eyes open; block 2: right hand/eyes open; block 3: left hand/eyes closed; and block 4: right hand/eyes closed. The trial order was randomized, and a new test paper was used for each trial. The participant was instructed to use their left or right hand with eyes open or closed depending on the trial condition. The participant was allowed 5 seconds to look at the target before being instructed to stamp a dot as close as possible to the target in 1 fluid motion using the specified hand. In the trials where the participant had their eyes closed, the participant looked at the target for 5 seconds and was then instructed to close their eyes and keep them closed while stamping the dot using the specified hand. The researcher immediately moved the test paper out of sight after each trial to minimize visual feedback. After completing 20 trials, participants were given a break to avoid fatigue or apathy. Each participant completed 2 sessions 1 week apart to simulate reasonable time between clinical visits.
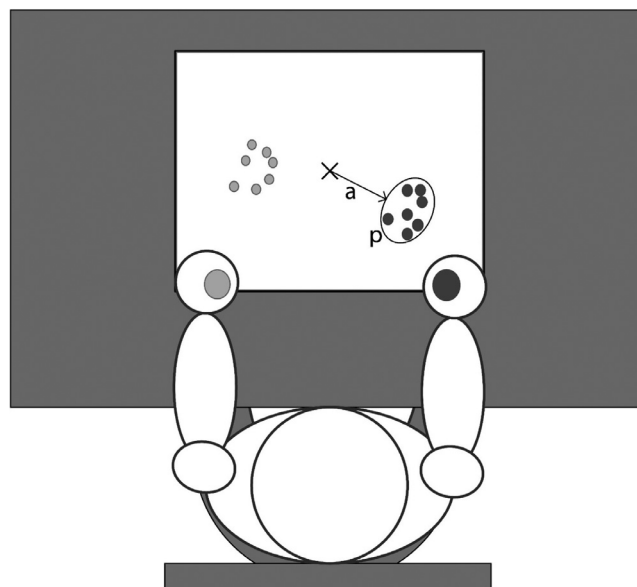

Fig. 1 Experimental setup with the participant seated at a table and the placement of the test paper. The close-up of the test paper shows the 2 measurements that were made: precision and accuracy. Abbreviations: a, accuracy; p, precision.

Data processing

After each session, all papers were scanned, and measurements of precision and accuracy (see fig 1) were made using a custom MATLAB[a] script. Precision was defined as targeting consistency, calculated from the minimum volume of the ellipsoid enclosing the area of the trials for each instructional block.[21] Accuracy was defined as the absolute distance between the target and the stamped dot.

Statistical analysis

To test our hypothesis that removing visual input, eyes-closed trials would decrease precision and accuracy compared with eyes open trials, paired t tests were conducted. To test our second hypothesis that completing the targeting task with the dominant hand will result in better accuracy than completing the targeting task with the nondominant hand, we used a TOST procedure for equivalence, which would identify whether accuracy between the dominant and nondominant hands are statistically different or equivalent.[22,23] The equivalence boundary for the eyes-closed comparison was set at $\pm$0.50 cm, calculated based on expected hand displacement while completing the targeting task and the commonly reported variability of 1° during proprioceptive testing.[15] The equivalence boundary for the eyes-open comparison was set at $\pm$0.10 cm because of the expected decrease in variability while completing the targeting task with eyes open compared with eyes closed.[24] Additionally, we calculated a dominance index defining the bias in accuracy between the dominant and nondominant hand, within eyes-open and eyes-closed conditions.[25] A positive dominance index indicated better accuracy with the dominant hand:

Dominance index

$$= \left(\frac{\text{Dominant hand accuracy} - \text{Nondominant hand accuracy}}{\text{Dominant hand accuracy} + \text{Nondominant hand accuracy}} \right) \\ * 100 \tag{1}$$

The minimum detectable change (MDC) method was used to assess test-retest reliability, with 95% confidence.[26] The square root of the mean square error term from a repeated-measures analysis of variance was used to estimate each instructional block's SEM. The MDC was calculated using the following equation:

$$MDC = SEM \times 1.96 \times \sqrt{2} \tag{2}$$

The MDC established a range around the first session mean to determine when the change between the first and second sessions was considered meaningful rather than measurement error.

The 30-minute assessment period for this study could be prohibitively long for clinical use. To decrease the assessment time and still obtain meaningful results, we calculated the precision and accuracy with only the first 3 trials up to the first 9 trials and compared these intermediate metrics with those from all trials in each instructional block. This allowed us to determine the minimum number of trials necessary for evaluation, within 10% of the final precision and accuracy.

Results

Participants

Twenty participants completed the test protocol (10 male, 10 female). Participants were right-hand dominant with a median age of 25 years (range, 19-33 years). All participants completed both sessions, and all trials were used for analysis.

Precision and accuracy of eyes open vs eyes closed during targeting

For the dominant hand condition the precision was better in the eyes-open vs eyes-closed condition, with means of 0.80 (range, 0.53-1.07) vs 8.92 (range, 7.39-10.45), respectively, and $P<.001$. For the nondominant hand condition the precision was better in the eyes-open vs eyes-closed condition, with means of 1.50 (range, 0.93-2.07) vs 11.00 (range, 9.01-12.99), respectively, and $P<.001$. For the dominant hand condition the accuracy was better in the eyes-open vs eyes-closed condition, with means of 0.14 (range, 0.10-0.18) vs. 2.45 (range, 2.10-2.80), respectively, and $P<.001$. For the nondominant hand condition the accuracy was better in the eyes-open vs eyes-closed condition, with means of 0.21 (range, 0.15-0.27) vs 2.34 (range, 2.05-2.63), respectively, and $P<.001$.

Accuracy of dominant hand vs nondominant hand use during targeting

For the eyes-open comparison of accuracy between the dominant and nondominant hands the TOST procedure for equivalence indicated that the observed effect size ($dz=0$) was not significantly within the equivalent bounds of -0.10 and 0.10 scale points, (or in Cohen's dz: -0.85 and 0.85), with $t(19)=-1.14$ and $P=.134$. For the eyes-closed comparison of accuracy between the dominant and nondominant hands, the TOST procedure for equivalence indicated that the observed effect size ($dz=0.14$) was significantly within the equivalent bounds of -0.50 and 0.50 scale points (or in Cohen's dz: -0.66 and 0.66), with $t(19)=-2.34$ and $P=.015$ (fig 2). These findings indicate that when completing the targeting task with eyes open there is a dominance effect, but when completing the targeting task with eyes closed the accuracy is equivalent between the dominant and nondominant hands.

Based on the accuracy dominance index, the eyes-open instructional blocks indicate better accuracy with the dominant hand (mean $\pm$ SE$=13.69\pm9.60$). In contrast, the eyes-closed instructional blocks indicate little to no difference in accuracy between hands (mean $\pm$ SD$=-1.41\pm3.75$), where on average, participants were slightly more accurate with the nondominant hand.

Test-retest reliability

The MDC range was centered around the mean accuracy for the first session and cut off at 0 for the minimum bound,

TOST Equivalence Test Between Non-Dominant and Dominant Hand in Targeting Accuracy

◄●► Mean (95% CI)   ┇ Equivalence Boundary
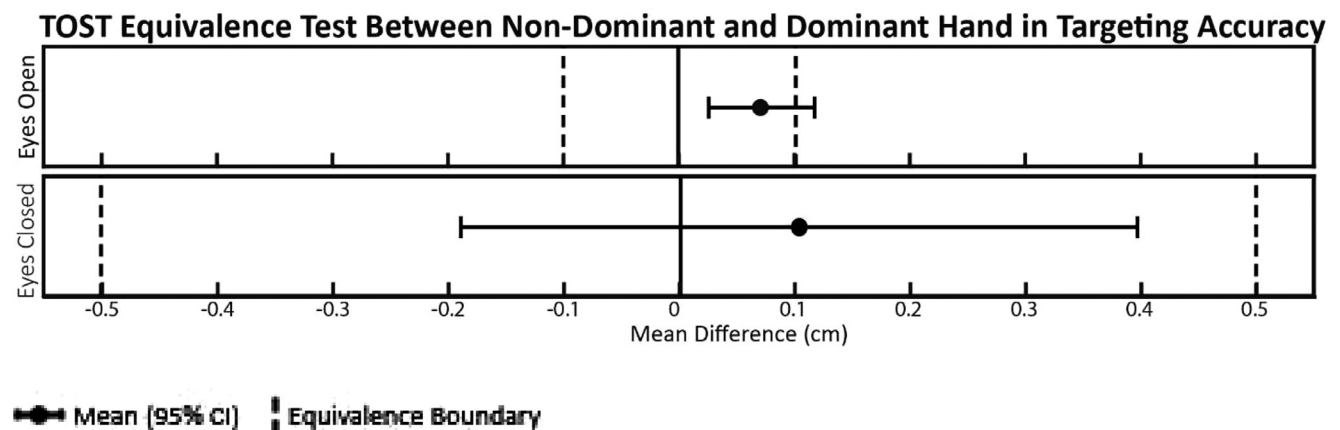
Fig. 2 TOST equivalence tests comparing the dominant and nondominant hands within the eyes-open and eyes-closed scenarios. The horizontal lines indicate the 90% confidence intervals from the TOST procedure. The solid vertical lines indicate the null hypothesis. The dashed vertical lines indicate the equivalence bounds (in raw scores). No statistical significance was found for either the eyes-open or the eyes-closed scenario for both the equivalence test and the null hypothesis.

Table 1 Precision and accuracy for each instruction block for the first session of all participants

Metric	Dominant Hand		Nondominant Hand	
	Eyes Open	Eyes Closed	Eyes Open	Eyes Closed
Precision (cm^2), mean (95% CI)	0.80 (0.53-1.07)	8.92 (7.39-10.45)	1.50 (0.93-2.07)	11.00 (9.01-12.99)
Accuracy (cm), mean (95% CI)	0.14 (0.10-0.18)	2.45 (2.10-2.80)	0.21 (0.15-0.27)	2.34 (2.05-2.63)

Abbreviation: CI, confidence interval.

when appropriate. The 95% confidence interval for the accuracy of each instructional block from the second session was entirely within the MDC range, indicating that any difference in accuracy from the first to the second session was because of random chance rather than a meaningful change in performance by the participant.

Least number of trials needed

To make this test more time-efficient, we identified the number of trials needed to represent the precision and accuracy. We made the representative cutoff of within 10% of the precision and accuracy when all trials were included from each instructional. Based on the instructional block, a range of 3-7 trials was needed to maintain representative precision and accuracy (table 3). To avoid confusion when using an abbreviated form of this assessment and using a conservative approach, we determined that 7 would be the least number of trials needed to represent precision and accuracy for a given instructional block.

Discussion

Our results supported the hypothesis that the UE proprioceptive targeting task will be sensitive enough to distinguish eyes open and eyes closed conditions, with a significant decrease in precision and accuracy when completing the targeting task with their eyes closed compared with eyes open, for both the dominant and nondominant hands. Our hypothesis that accuracy will be equivalent between the dominant and nondominant hands when relying on proprioception, which allows for within-participant control measurement, was supported. The TOST procedure for equivalence did not indicate equivalence between the dominant and nondominant hand during the eyes-open condition but did indicate equivalence during the eyes-closed condition. These results suggest that when targeting with eyes closed, the dominant and nondominant hands could be used as a control for the other. In addition to

the TOST procedure for equivalence, we calculated a dominance index to be used on an individual level for measuring a dominance effect, which is especially relevant for future work in patient populations. Our objective to show that repetition of the targeting task without intervention would not affect precision or accuracy changes was supported. For each instructional block, the second session precision and accuracy were within the MDC range based on session 1. This finding held at the group and individual levels, indicating that any variation in results between sessions could be attributed to random chance rather than a meaningful change in precision and accuracy. Finally, we demonstrated maintenance of representative results (within 10%) with decreased number of trials, from 10 to 7 trials per instructional block. Recommending completing only the eyes-closed trials in the clinical setting reduces the total number of trials from 40 to 14 and eliminates the need for breaks to mitigate fatigue or apathy during the assessment. These changes would substantially decrease the time to complete this assessment for better adaptation to a clinical setting.

The development of this assessment was motivated by a lack of methods applicable to testing EPP in the UE. EPP is the extension of proprioception outside of the body to a simple tool and serves as an indicator of spatial control over an external device.[4] Based on the initial results of this study, we plan to apply the same methodology to individuals with amputation, specifically those with and without OI, as a functional metric of control over their prosthetic device. Control over a prosthetic device is an important metric because a lack of control over it has been reported as a primary reason for decreased use or abandonment of a prosthesis.[13]

Fatigue has been found to affect proprioceptive accuracy negatively,[7] so the target was placed within the same horizontal plane as the starting point of the hand to minimize muscle use and fatigue throughout the targeting task.[20] Additionally, limiting the vertical motion required to complete the task makes the targeting task more attainable for the larger population, notably concerning the limited

Table 2 Test-retest reliability as measured by the MDC, based on accuracy between the first and second sessions

Metric	Dominant Hand		Nondominant Hand	
	Eyes Open	Eyes Closed	Eyes Open	Eyes Closed
Session 1 average accuracy (cm), mean (95% CI)	0.14 (0.9-0.19)	2.45 (2.06-2.84)	0.21 (0.15-0.27)	2.34 (2.02-2.66)
Session 2 average accuracy (cm), mean (95% CI)	0.19 (0.13-0.25)	2.25 (1.82-2.68)	0.20 (0.14-0.26)	2.24 (1.87-2.61)
SEM (cm)	0.06	0.52	0.09	0.48
MDC (cm)	±0.18	±1.44	±0.25	±1.33
MDC (cm), range	0-0.32	1.01-3.89	0-0.45	1.01-3.67

Abbreviation: CI, confidence interval.

Table 3 Average least number of trials needed across all participants for each block to achieve precision and accuracy within 10% of nominal

Least Trials		Eyes Open		Eyes Closed		Overall Least No. of Trials
		Dominant Hand	Nondominant Hand	Dominant Hand	Nondominant Hand	
Representative Precision	Session 1	5.25	5.05	6.15	5.65	7
	Session 2	6.2	5.7	6.55	5.4	7
Representative Accuracy	Session 1	5.2	4.9	4.2	3.7	6
	Session 2	4.0	4.65	3.75	2.95	5

shoulder range of motion resulting from the use of a conventional socket prosthesis.

The UE proprioceptive targeting task in this assessment requires active positioning of multiple joints and body segments, including but not necessarily limited to the wrist, elbow, shoulder, and trunk. Because the test setup did not restrict the participants' arm or torso movement while completing the targeting task, participants completed the task as they would outside of the laboratory.[20] This is especially important when considering translation into the population of interest, UE prosthesis users. In addition to the effect of the socket on shoulder range of motion, UE limb loss has a high correlation with shoulder pain, which may indicate other orthopedic conditions.[27] Allowing free movement when completing the targeting task accounts for these limitations, enabling individuals to accommodate with more proximal joints to achieve distal accuracy.

We hypothesized that the UE targeting task is measuring proprioception if it is sensitive enough to distinguish between the eyes-open and eyes-closed targeting conditions. A review of proprioception measurement methods found that a common strategy was excluding vision to produce reliance on proprioception during testing.[15] This finding points to the importance of obscuring vision while testing proprioception, supporting our claim that this assessment is measuring proprioception in the eyes-closed condition. The claim is further supported by the decrement in targeting accuracy from the eyes-open to the eyes-closed targeting conditions, which follows the known relationship between visual input and proprioception.[2,3,28]

The motivation for understanding EPP between the dominant and nondominant hands relates to assessing persons with unilateral amputations and using the intact limb as a control for the affected limb. Similarly, proprioceptive sensitivity in shoulders between healthy and rehabilitated shoulders is not significantly different.[29] The accuracy dominance index[25] supports the idea that when relying on proprioception during the eyes-closed trials, there is little to no bias in accuracy based on which hand is completing the targeting task. We emphasized the dominance index of the eyes-closed trials because eyes-open trials used dual systems—proprioception and vision—diminishing the effect of proprioception. Based on this accuracy dominance index, using the intact limb as a within-participant control for the affected limb is reasonable.

Test-retest repeatability was demonstrated using the MDC method. This comparison method allows for a comparison between sessions at the individual level rather than the population. Individual comparisons are valuable for

clinicians monitoring and quantifying change at a patient-specific level.[30] The normative values presented in this study establish an MDC range, which can be used individually in a clinical setting.

Future work will include participants 60 years and older to establish an elderly baseline of EPP. The work presented in this article supports the use of this assessment, and future work will reflect the recommended changes, such as decreased number of trials. For this assessment, we will recruit elderly participants using the same initial exclusion criteria. Once young adult (18-60 years) and elderly adult (60 years and older) baselines have been established, patients with transhumeral, transradial, and hand amputations using prosthetic devices will be tested to ensure that this method can be completed with a prosthesis to observe changes in accuracy or directional bias within and between sessions using EPP as well as to understand how the symmetry is affected between the prosthetic and contralateral limb. It will be critical to work with patients to adjust the tip of the pen in their grasp to account for individual perceptions of the prosthesis. Using a pen will standardize the targeting strategy between participants by consistently defining a distal point to target with.[31]

Study limitations

The targeting task in this assessment was limited to horizontal movement to reduce muscular fatigue that diminishes proprioceptive acuity and to make the targeting task more attainable when translated to the larger population.[32] Although some vertical movement to lift and lower the UE to mark the paper was performed, we did not determine if the results of this test have a strong relationship with larger vertical plane motions, and further research should be performed in this area. An additional limitation in this study is that individual joint contributions to the targeting task were not quantified, including the motion of the trunk. To make this assessment a functional measurement, we did not limit any joint motion. Still, some measures of multijoint proprioception indicate that there is variable proprioceptive acuity between proximal and distal joints.[33] This disparity may be exacerbated in individuals using prosthetic devices where the distal joints are less likely to be adjusted during the targeting task. Limitations of this study include the participants' age because only a young adult population was included for analysis and establishment of the baseline. Because age negatively affects proprioception, especially in compensating for errors in carrying out movements,[17,18] further research should be performed in an older cohort, older

than 60 years. We have not yet applied this assessment to patients using UE prostheses or with a UE pathology. Additionally, the time to complete the assessment in our laboratory setting is not conducive to a clinical setting. Even with the recommendations to reduce the number of trials, the assessment may be too lengthy, 15 minutes including set up and instructions, to incorporate into standard clinical visits. Finally, our analysis required the trial papers to be scanned to complete the measurements with the custom MATLAB script as described in the methods. While pen and paper make it possible to complete this assessment anywhere, these analysis methods may be inaccessible in a clinical setting. To overcome this, phone applications could be used to scan the hard copies for analysis through the custom MATLAB script, or a tablet application could be developed to automate the entire assessment.

Conclusions

The results of this study support both hypotheses. This assessment is sensitive enough to distinguish between the eyes-open and eyes-closed conditions, verifying measurement of proprioception and that there is symmetry between the dominant and nondominant hands to allow for within-participant control. Test-retest reliability was established, as was the rationale for shortening the assessment for feasible clinical adaptation. While these results support the feasibility of using this assessment to measure EPP, additional research needs to be done in a clinical population to further evaluate the UE proprioceptive targeting task assessment and collect objective data on EPP.

Supplier

a. MATLAB version 9.10.0 (R2021a); MathWorks Inc, Natick, MA.

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