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Reachable Workspace and Performance of Upper Limb (PUL) in Duchenne muscular dystrophy

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Abstract

Introduction—The Kinect-based reachable workspace relative surface area (RSA) is compared with the Performance of Upper Limb (PUL) assessment in Duchenne muscular dystrophy (DMD).

Methods—29 individuals with DMD (ages: 7–23, Brooke: 1–5) underwent both Kinect-based reachable workspace RSA and PUL assessments. RSAs were also collected from 24 age-matched controls. Total and quadrant RSAs were compared with the PUL total, shoulder-, middle-, and distal-dimension scores.

Results—The total reachable workspace RSA correlated well with the total PUL score (Spearman $\rho=-0.602$, $P<0.001$), and with each of the PUL dimensional scores: shoulder ($\rho=-0.624$, $P<0.001$), middle ($\rho=-0.564$, $P=0.001$), and distal ($\rho=-0.630$, $P<0.001$). With quadrant RSA, reachability in a particular quadrant was closely associated with respective PUL dimensional-level function (lateral-upper quadrant for shoulder-, lateral-upper/lower quadrants for middle-, and lateral-lower quadrant for distal-level function).

Discussion—This study demonstrates concurrent validity of the reachable workspace outcome measure (RSA) with the DMD-specific upper extremity outcome measure (PUL).

Keywords/MESH terms

Reachable workspace; PUL; DMD; upper extremity; Kinect

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INTRODUCTION

In Duchenne muscular dystrophy (DMD), there are a limited number of viable upper extremity functional assessment tools and outcome measures compared to available lower extremity measures.[1,2] This lack of upper extremity outcome measures is particularly relevant for DMD because despite relatively early loss of ambulatory function, most individuals with DMD maintain upper extremity function for a prolonged time with progressive decline throughout the course of the disease and lifespan.[3] In response to this recognized need to develop a better upper limb outcome measure, not only to track disease progression but for use in efficacy testing of promising therapeutics in clinical trials, novel approaches are actively being explored by researchers. Two of the innovative approaches are the Performance of Upper Limb (PUL)[4,5] assessment and the Kinect sensor-based 3-dimensional (3D) upper extremity reachable workspace analysis system.[6,7,8]

The PUL was developed specifically for DMD and is capable of assessing a wide-spectrum of upper extremity function in both ambulant and non-ambulant individuals with DMD.[4] The PUL was designed with a conceptual framework reflecting the progression of weakness and natural history of functional decline in the disease.[4] Modern psychometric methods were used to create a scale with robust internal reliability, validity, and hierarchical scalability; males with DMD and their families were involved iteratively throughout clinician-reported outcome (ClinRO) development process to relate clinical meaningfulness of individual PUL items to activities of daily living (ADL). The PUL provides a total upper extremity functional score capable of characterizing overall progression and severity of disease, while its component subscores, which assess the 3 major level dimensions (shoulder-, middle-, and distal-levels), can track the stereotypical proximal-to-distal progressive loss of upper limb function in DMD. In a recent large multicenter study, the PUL was shown to be capable of reliably assessing upper extremity function in both ambulant and non-ambulant children and adults with DMD.[5]

Recently, the Kinect sensor-based upper extremity reachable workspace analysis system and its outcome measure (total and quadrant reachable workspace envelope relative surface area, RSA) has also demonstrated utility and potential as a novel upper extremity outcome measure in DMD.[6] The sensor-acquired reachable workspace measure reliably captured a wide range of upper limb impairments across the dystrophinopathy spectrum in both children and adults with DMD/BMD, as well as ambulatory and non-ambulatory individuals.[6] Furthermore, the reachable workspace RSA not only correlated well with Brooke upper extremity functional grades, but a progressive reduction in RSA also directly reflected clinically meaningful person-reported outcomes (PROs) that represented an individual’s decline in ability to perform ADLs (using the upper extremity domain questionnaire of the NeuroQOL).[6]

A systematic comparison of these 2 new upper extremity outcome measures in DMD has not been done and would be informative for designing future clinical trials in non-ambulatory and late ambulatory stages of DMD, where each may play complementary roles. In this study, we focus on better understanding the relationship between the PUL and the Kinect-based reachable workspace RSA. In particular, we will assess the relationships between the total and quadrant reachable workspace RSAs and the total PUL score as well as the major dimension level subscores of the PUL (shoulder-, middle-, and distal-levels).

MATERIALS AND METHODS

Study Participants

A total of 53 subjects (29 boys and adult men with DMD and 24 age-matched healthy controls) participated in the study. All participants with DMD had genetic confirmation of mutations in the *dystrophin* gene with clinical features congruent with the diagnosis. Demographic and anthropometric data (age, height, weight, and ambulatory status) were obtained from each subject. The study protocol was approved by the University Institutional Review Board (IRB) for human clinical research. The healthy control subjects were recruited from the surrounding regions through the IRB-approved notification and advertisement methods.

Performance of Upper Limb (PUL)

The PUL total score and major level dimensional subscores (shoulder-, middle-, and distal-levels) were collected from all subjects following the previously published methods.[4,5] The study evaluators underwent specific training for administration of the PUL. Briefly, the PUL assessment was performed unilaterally on the side of preference (typically the dominant arm) following the established PUL protocol. The tested side (whether right or left, dominant or non-dominant) was noted for analysis. The PUL includes a total of 22 upper limb test items, with the first entry item (A) used to define the starting functional level. The remaining 21 items (B-V) are subdivided into 3 major dimension levels (shoulder-4 items; middle-9 items; distal-8 items). On each test item, scores can range from 0–1 or 0–6 depending on the subject's performance, with higher score denoting better function. Each dimension level is scored separately, with a maximum score of 16 for the shoulder level, 34 for the middle level, and 24 for the distal level. Adding the 3 dimension-level subscores yields the total PUL score (maximum total score=74). In addition, the PUL timed performance tests (in seconds, 4 separate tests comprised of lifting and stacking 5 light and heavy cans) were also recorded.

Reachable Workspace Relative Surface Area (RSA)

The reachable workspace protocol followed previously published methods.[6,7] The subjects were seated in front of the Kinect sensor (Microsoft Corp., Redmond, WA, USA) and underwent a standardized upper extremity movement protocol. The protocol typically took about 1 minute per arm to complete. Although bilateral RSA data were collected, only the corresponding side (either right or left) for which the PUL was performed was used for analysis. Once the Kinect-acquired 3D upper extremity motion trajectory was collected, each individual's reachable workspace surface envelope was reconstructed using the methods described previously.[6,7] The reachable workspace envelope for the tested arm was further divided into 4 quadrants (upper medial and lateral, lower medial and lateral) with the respective shoulder joint serving as the origin (Figure 1). The quadrant enumeration 1–4 is relative to each tested arm (1-medial upper; 2-medial lower; 3-lateral upper; 4-lateral lower). The absolute total and quadrant reachable workspace surface envelope areas (m^2) were calculated and normalized by each individual's arm length to obtain the relative surface area (RSA).[6,7] This RSA representing the portion of a frontal unit hemi-sphere, is determined by dividing the absolute reachable workspace area by the factor $4\pi r^2$ x (1/2), where r represents the arm length. This provides normalization of the data by each individual's arm length to allow comparison between subjects. For test-retest reliability/reproducibility assessment, subjects were tested on the same day of the evaluation for repeated data collection.

Statistical Analyses

Statistical analyses utilized SAS 9.4 software. Data were checked for normality through the Shapiro-Wilk test. Spearman and Pearson correlation analyses were used for non-parametric and parametric data respectively. Student *t*-tests were used to assess differences between 2 groups. ANOVA was used to assess differences between multiple groups, and a *post-hoc* Tukey test was used to determine sub-group differences. Stepwise regression analysis was performed for identification of determinant factors. For all statistical analyses, a minimum *P*-value of 0.05 was accepted as the level of statistical significance; however, specific *P*-values are reported in this study.

RESULTS

Study participant demographics

Demographics and description of the study participants including age, ambulatory status, side-tested (25 right and 4 left), and PUL scores (total, shoulder-, middle-, and distal-levels) are shown in Supplemental Table S1, available online. The average age of the DMD cohort was 11.7 ± 3.48 years, with range of 7.3 to 22.8 years. Thirteen of the 29 DMD participants were non-ambulatory at the time of testing. The healthy control group consisted of 24 age-matched boys and adult men (average age: 13.5 ± 5.47 years, range 6.5 to 22.6 years). There was no significant age difference between the DMD and control cohorts. We observed a small, but significant, difference in the heights of the DMD patients (139.7 cm ± 20.21) and the controls (155.4 cm ±22.7), P=0.01.

Test-retest reliability of Kinect-acquired reachable workspace (RSA) in DMD

The test-retest reliability of the Kinect-acquired 3D reachable workspace RSA in the study DMD group (n=38, representing 19/29 subjects for both right and left arms) demonstrated a Pearson correlation coefficient of R=0.934 ($P<0.0001$) and ICC=0.935 ($P<0.001$). For the PUL, the inter-rater reliability has already been demonstrated to be high (ICC=0.96) by Pane et al.[5]

Study DMD cohort Performance of Upper Limb (PUL) data

Before comparing the study DMD cohort Kinect-based reachable workspace measures with the collected PUL data, we wanted to first assess the cohort's PUL data characteristics and spectrum of disease severity. We wanted to assess whether our DMD study cohort's (n=29) composition and range of disease severity was similar to that reported by Pane et al. in a recent large sample size study (n=322).[5] Our DMD study cohort's mean total PUL score was 60.3 ± 18.1 (range: 13 to 74) and PUL shoulder level subscore was 9.69 ± 5.9 (range: 0 to 16). Six of 29 subjects received a PUL entry score of <4 and therefore started the evaluation at item F. For those 6 subjects, the PUL shoulder-dimensional subscore was effectively recorded as 0. The DMD cohort's middle-dimension subscore was 28.2 ± 10.3 (range: 1 to 34), and the distal-dimension subscore was 22.4 ± 3.0 (range: 11 to 24). The average times to complete the PUL tasks were: lifting 5 light cans, 4.47 ± 0.69 seconds (range: 2.97 to 6.56); lifting 5 heavy cans, 5.28 ± 1.51 seconds (range: 3.15 to 10.09); stacking 5 light cans, 6.99 ± 1.20 seconds (range: 4.94 to 8.94), and stacking 5 heavy cans, 8.24 ± 1.52 seconds (range: 5.78 to 11.35). Graphical representation of the DMD cohort's PUL total score, shoulder-, middle-, and distal-level subscores by age is shown in Figure 2. Overall review of the data reveals similar composition, age range, ambulatory status, range of upper extremity impairment, and disease severity spectrum between this study's DMD cohort and the cohort reported by Pane et al.[5]

Reachable workspace by PUL entry item score

The score on the PUL entry item (A) determines the starting point for subsequent tests (whether to start at the shoulder- or middle-level) and is a differentiating point for the PUL assessment to separate those who have less upper limb impairment (scores 4–6) from those who are more severely affected (scores 0–3). In our DMD study group, 23 of the 29 received entry PUL score of ≥4 (less affected) compared to 6 subjects who received a score <4 (more affected). No subject was represented by an entry PUL score of 2. Representative graphical illustrations of reachable workspace in a young healthy control boy (age 7 years) and 5 DMD subjects (with PUL entry item scores of 1–6, with exception of 2) are shown in Figure 3.

An ANOVA analysis revealed that the total reachable workspace RSA is highly associated with upper extremity impairment as determined by the PUL entry item score ($F_{1,29}$ = 228.95; P<0.0001). A reachable workspace plot and bar graph for DMD subjects categorized by the PUL entry item score demonstrates progressive reduction of reachable workspace RSA due to worsening upper extremity impairment (Figure 4 A–B).

Correlation between total RSA and PUL scores (total, shoulder-, middle-, distal-levels)

The correlations between the DMD group Kinect reachable workspace total RSA and the PUL total score as well as the dimensional subscores (shoulder, middle, distal) are shown in Figure 5 A–D using Spearman rho (ρ) correlations due to the ordinal nature of the PUL scale. Although bilateral reachable workspace RSA data were available, only the side corresponding to the side that underwent PUL evaluation was selected for the RSA analysis (n=29). The overall correlation between the total RSA and the total PUL score was relatively high (ρ=−0.602, P<0.001). A preliminary evaluation of the PUL by its developers using Rasch analysis has shown evidence for linearity of the outcome measure.[4] Thus, if the Pearson correlation method is utilized, the total RSA and total PUL also have a very strong correlation (R= 0.945, P<0.001). The correlation between the total RSA and the subscores of the PUL 3 component dimensional levels also demonstrated relatively high correlation for all levels: shoulder-level (ρ=−0.624, P<0.001), middle-level (ρ=−0.564, P<0.001), and distal-level (ρ=−0.631, P<0.001).

Correlation between total RSA and PUL timed tests

The correlation between the DMD group total RSA and the PUL timed items showed no significant correlations for lifting light or heavy cans, or for stacking light or heavy cans (Supplemental Figure S1, available online). Evaluation of the quadrant RSAs and the PUL timed items also showed no significant correlations except for the lateral lower quadrant (quad 4) with light (R=−0.440, *P*=0.032) and heavy (R=−0.578, *P*=0.005) can lifting (Supplemental Figure S2, available online).

Correlation between quadrant RSA and PUL dimensional scores

For each respective dimensional level, an average score for each subject was obtained. Using these average shoulder-, middle-, and distal-level scores, correlations with each quadrant RSAs were examined. The respective Pearson correlation coefficients between each of the quadrant RSAs (1–4) and the average PUL dimensional scores (shoulder, middle, and distal) are shown (Table 1). Additionally, a stepwise regression analysis was done to identify which of the quadrants corresponded best with each of the PUL dimensional scores. For the shoulder level function, the lateral upper quadrant (quad 3) was the most important determinant of the PUL shoulder dimension scores (R=0.867, *P*<0.001). For the middle level, again the lateral upper quadrant (quad 3) was most predictive of the PUL middle dimensional scores (R=0.956, *P*<0.001); however, the lateral lower quadrant (quad 4) also correlated highly, essentially to the same degree (R=0.938, *P*<0.001). For the distal level, the lateral lower quadrant (quad 4) had the highest correlation with the PUL distal dimensional scores (R=0.800, *P*<0.001). The most correlative quadrants for each of the PUL dimensions (shoulder, middle, distal) are represented on the reachable workspace plot by their respective colored quadrant (Fig. 6).

Correlation between quadrant RSA and PUL individual items (B-V)

The scores on each of the individual PUL component clinical evaluator-determined items (B-V) were examined for significant correlations with quadrant RSAs. Mapping each of the PUL items B-V, respective of reachable workspace quadrants based on correlation coefficients (Spearman) is shown in Figure 6 in addition to the rank order of difficulty of PUL items according to a previously reported Rasch analysis with items listed in order of difficulty (from easiest to more difficult as determined by Mayhew et al.[4]). For each of the shoulder-dimension items (B-E), highest correlations were noted with quadrant 3. The middle-dimension items were split between quadrants 3 and 4 (for items J, K, L, to both quadrant 1 and 3 equally, while for items F, G, I, M, N, to quadrant 4 alone, and for item H, only to quadrant 3). For the distal-dimension, items P and Q correlated highly with quadrant 2, while the items R and S correlated highly with quadrant 4. The individual PUL items O, T, U, and V did not correlate significantly with any quadrant RSAs (Note: items T, U, and V were added in a later version of the PUL to reduce its floor effects[4]).

DISCUSSION

In a series of recent studies,[6,7,8,9,10,11,12] the utility of a novel upper extremity reachable workspace outcome measure, acquired using a 3D vision-based sensor, have demonstrated promising potential in various neuromuscular disorders. Specifically in DMD, the Kinect sensor-based reachable workspace relative surface area (RSA) has been demonstrated to be applicable, reliable, and valid in both pediatric and adult populations with DMD, as well as ambulatory and non-ambulatory individuals with a wide range of upper limb impairment.[6] In this study, the relationship between the reachable workspace and another innovative upper extremity outcome measure, the PUL,[4,5] which was "specifically-designed" for DMD clinical studies, is examined.

As a global measure of upper extremity function, the reachable workspace of an individual depends largely on the combination of range of motion and strength measures at the shoulder and elbow levels.[6,9,10] However, it makes sense intuitively that the reachable workspace would not be as tightly related to the distal upper limb (hand and wrist) function. The preferential association between proximal upper limb function and the reachable workspace outcome measure is particularly useful in a variety of neuromuscular conditions (including DMD), where proximal-to-distal progression of disease with relative sparing of distal hand function is the typical pattern, and where loss of hand/wrist function is not a prominent feature until much later in an advanced stage of the disease.[3,5,13]

The PUL has been developed specifically for DMD, taking into consideration the natural history of the disease as well as the contributions of shoulder-, middle-, and distal-dimensions to overall upper extremity function.[4] A recent large DMD cohort study (n=322) has demonstrated the validity and reliability of the PUL measure.[5] However, prior to comparing the reachable workspace RSA to PUL in our DMD cohort (n=29), we first wanted to make sure that the DMD cohort reflected similar composition of age and disease severity with the larger DMD cohort reported by Pane et al.[5] Although smaller in sample size, our study's DMD cohort had a similar composition by both age and distribution of upper limb impairment as that presented in the larger cross-sectional DMD population (Figure 2). This establishes that the study's findings can be translated to the DMD population at large.

Since the reachable workspace reflects proximal upper extremity function, we first evaluated the correlation between the PUL entry item score and the reachable workspace total RSA. As expected, the total RSA correlated extremely well with the PUL entry item score and could differentiate those who received the PUL entry score 4–6 from those who received 0–3. Additionally, the total RSA correlated very well with the PUL total score, as well as with the shoulder-, middle-, and distal-level subscores (Figure 5A–D). The strong relationship between the Kinect-acquired RSAs and PUL total as well as the dimensional scores provides concurrent validity and clinical meaningfulness of total and specific quadrant RSA measures.

Interestingly, an in-depth examination of the quadrant RSAs with PUL dimensional subscores yielded significant associations. In the shoulder dimension, the lateral upper quadrant RSA (quadrant 3) correlated well with the PUL shoulder items C and E (corresponding to shoulder abduction and flexion to eye level, respectively), both of which were found to be the most difficult tasks by Rasch analysis. Quadrant 3 also correlated well with shoulder abduction and flexion to shoulder level (items B and D, the next most difficult items by Rasch analysis). Thus, the lateral upper quadrant RSA (quadrant 3) measures *clinically-meaningful* changes in disease progression of DMD subjects identified by the PUL, specifically with regard to proximal shoulder girdle strength and range of motion affecting functional activities in the shoulder dimension.

In the middle dimension, both the lateral upper and lower quadrant RSAs (quadrants 3 and 4) correlated well with PUL middle-level items. Quadrant 3 RSA had the highest correlations with 3 out of 4 PUL items deemed to be the more difficult of the elbow dimension items by Rasch analysis (H: Move weight on table; L: Stacking heavy cans; and J: Lifting heavy cans). Similarly, the lateral lower quadrant RSA (quadrant 4) had highest correlations with 4 of the 5 PUL middle dimension items deemed to be less difficult relative to the other middle dimension items [G: Hand(s) to table from lap; N: Tearing paper; I: Lifting Light cans; and M: Remove lid from container] based on the published Rasch analysis of difficulty of middle-dimension PUL items.[4]

While it makes sense intuitively that the reachable workspace would not be as tightly related to the distal upper limb (hand and wrist) function, this study's findings indicate that the reachable workspace RSA in the lateral lower quadrant (quadrant 4) was surprisingly well-correlated with 2 of the PUL items which were deemed relatively less difficult by Rasch analysis (R: Picking up coins, and S: Placing finger on number diagram). Similarly, the medial lower quadrant RSA (quadrant 2) was correlated with the 2 most difficult items on the distal dimension of the PUL (Q: Turning light, and P: Pushing on the light). The individual PUL items O, T, U, and V did not correlate significantly with any quadrant RSAs. This is not surprising given the content of these items. For example, PUL item O (tracing path) measures the ability to pick up a pencil from desktop and to trace a prescribed path with or without stops and with or without raising the hand from the paper. Items T, U, and V were added in a later version of the PUL to reduce floor effects for some of the most severely affected subjects.[4]

With regard to the other RSA quadrants, the upper quadrant RSA (quadrant 1) appears to be responsive to changes in disease progression from Brooke 1 to Brooke 2 grades, responsive to changes seen in more mildly affected Becker muscular dystrophy (BMD) patients versus controls, and to changes in DMD patients undergoing a loading protocol with 500g and 1000g wrist weights.[6] Thus, both consideration of quadrant 1 (upper medial quadrant) and addition of loading protocols to the Kinect-based reachable workspace protocol may be helpful in terms of addressing the ceiling effects observed with the PUL in ambulatory DMD subjects. While upper limb involvement can already be found in DMD boys in the ambulant phase, the use of the PUL appeared to be less relevant in very strong subjects with DMD and 6-minute walk distance (6MWD) above 400 meters, who with few exceptions had near-full scores.[14]

In DMD, there is a strong physiological rationale for the benefit of earlier treatment, as therapies that preserve muscle are likely to have the greatest impact on prognosis before muscle health has deteriorated.[14] Thus, the shoulder- and middle-level dimensions of the PUL as well as the 2 upper quadrants (medial 1 and lateral 3) and lateral lower quadrant (4) RSA values hold particular importance for future non-ambulatory clinical trials. The greatest benefit of a therapy in non-ambulatory subjects with DMD will likely occur earlier in the course of disease subsequent to loss of ambulation, at a time when upper quadrant RSAs and lateral lower quadrant RSA along with shoulder-level and middle-level dimensions of the PUL likely show the greatest decline with disease progression.

The Kinect-determined RSA did not correlate with the timed functional parameters assessed by the PUL. However it is important to note that for time taken to perform the individual PUL items (I, J, K, L) in typically developing and in DMD boys and young adults, there was a marked overlap between the typically developing and DMD cohort until age 10 years.[5] The strength of the relationship between time spent to stack or lift cans of varying weight and disease progression in DMD remains to be determined.

The protocol devised for this sensor-based assessment of bilateral reachable workspace RSAs purposely isolates each upper extremity during testing, and it attempts to limit as much as possible additional confounding motion contributions from other body regions. The subjects perform a standardized and sequential movement protocol that encompass all cardinal motions of the shoulder that contribute to reachable workspace, and specific instructions are given to the subjects not to lean, laterally bend, flex, extend, or rotate the trunk. This approach has its rationale in the underlying original goal to develop a quantitative, reliable, valid, and meaningful measure of upper extremity function and functional reachable workspace, as opposed to a combined measure of upper limb and trunk motion to achieve functional reach. It was felt that elimination of compensatory trunk motions would simplify analysis for important determinants/factors for upper limb reachability without having to consider additional complicated motion contributions from truncal movements (flexion, extension, lateral bend, rotation), and also enhance standardization when the measure is extended to multi-center clinical trials.

In addition, since a significant percentage of non-ambulatory DMD subjects develop scoliosis which may require spinal arthrodesis (>80–90%),[13,15] the hope was to not eliminate the quantitative upper limb measures among those subjects who require subsequent surgical management of spinal deformity or who previously underwent spine fusions. Essentially, an upper limb reachability outcome that incorporates and necessitates truncal motion would pose significant analysis difficulties due to incompatibility of data pre- and post-spine stabilization surgery. However, we recognize that some functional activities performed by subjects with DMD utilize trunk motions as compensatory maneuvers to place the extremity in a more biomechanically efficient orientation in order to complete functional tasks with the ipsilateral upper limb. In addition, at times adolescents and adults with DMD use their contralateral extremity to assist the ipsilateral upper limb in order to complete functional activities in the setting of significant weakness that is less than antigravity. Thus, while recognizing and appreciating that an individual with DMD in real life may use a combination of trunk motion and assistance by the contralateral extremity to aid in reaching the ipsilateral hand to the mouth or scalp, a “standardized upper extremity clinical outcome measure” does not necessarily have to conform to incorporating all these compensatory maneuvers as long as it can accurately capture/track functional capability and predict function.

One of the additional inherent limitations of the reachable workspace outcome measure is that extension of the data to functional activities assumes preserved hand function. While a key functional requirement is that the hand be placed in a critical position for completion of a functional task, the RSA does not actually assess the functional dexterity of the hand and fingers in order to complete a fine motor task. For example, placing the hand to the keyboard of a typewriter or computer mouse may be functionally relevant and can be assessed by the Kinect-based RSA, but the RSA does not measure actual ability of the hand to type or functionally use a standard computer mouse or track pad. However, the study findings suggest that, at least in DMD (due to its stereotypical and relatively tight association between decline of proximal and distal upper limb functions), the reachable workspace RSA nevertheless can provide informative data about distal upper limb function. It is likely that for more comprehensive assessment of upper limb function in DMD, a complementary approach incorporating both reachable workspace and other distal function-specific outcome measures may be optimal.

CONCLUSION

Although most clinical trials in DMD to date have focused on ambulatory patients, there is a broad international consensus to develop a range of outcome measures that could be used across both ambulatory and non-ambulatory individuals with DMD.[16] There is a critical need to develop transitional measures that can serve as a bridge across different age groups, functional abilities, and milestones such as the transition from ambulation to non-ambulation. The sensor-based quantitative reachable workspace measure holds promise as a clinically meaningful endpoint for clinical trials that target late ambulatory children, non-ambulatory children, and adults with DMD.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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ABBREVIATIONS

3D	Three-dimensional
ADL	Activities of daily living
ANOVA	Analysis of variance
BMD	Becker muscular dystrophy
ClinRO	Clinician reported outcome

DMD	Duchenne muscular dystrophy
NeuroQOL	Neurological Disorders Quality of Life
PRO	Person-reported outcome
PUL	Performance of Upper Limb
RSA	Relative surface area

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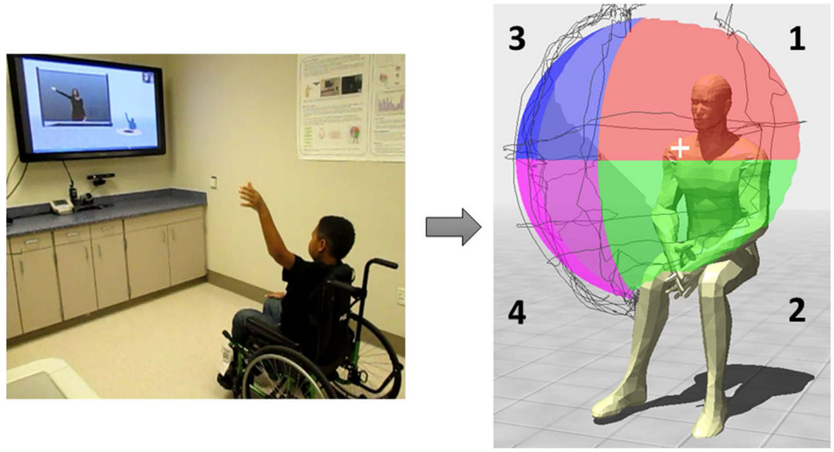

Figure 1.

Picture of Kinect evaluation for reachable workspace. An example graphical output of 3D reachable workspace is shown with enumerated quadrants 1–4 (in the right upper extremity perspective).

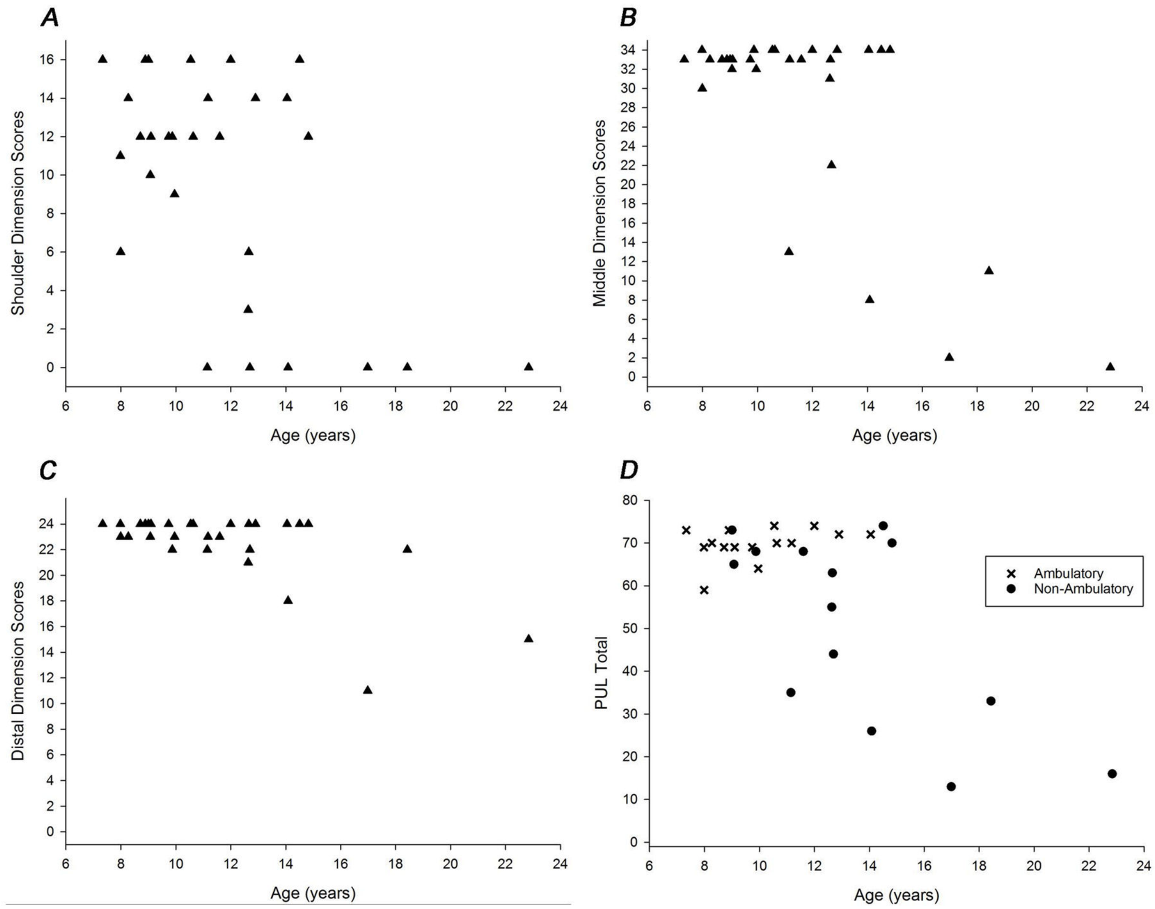

Figure 2.

PUL scores for the study subjects. Distribution of scores for study subject shoulder- (A), middle- (B), and distal- (C) dimensions. Distribution of total PUL scores in ambulant (X) and non-ambulant (●) DMD subjects by age (D).

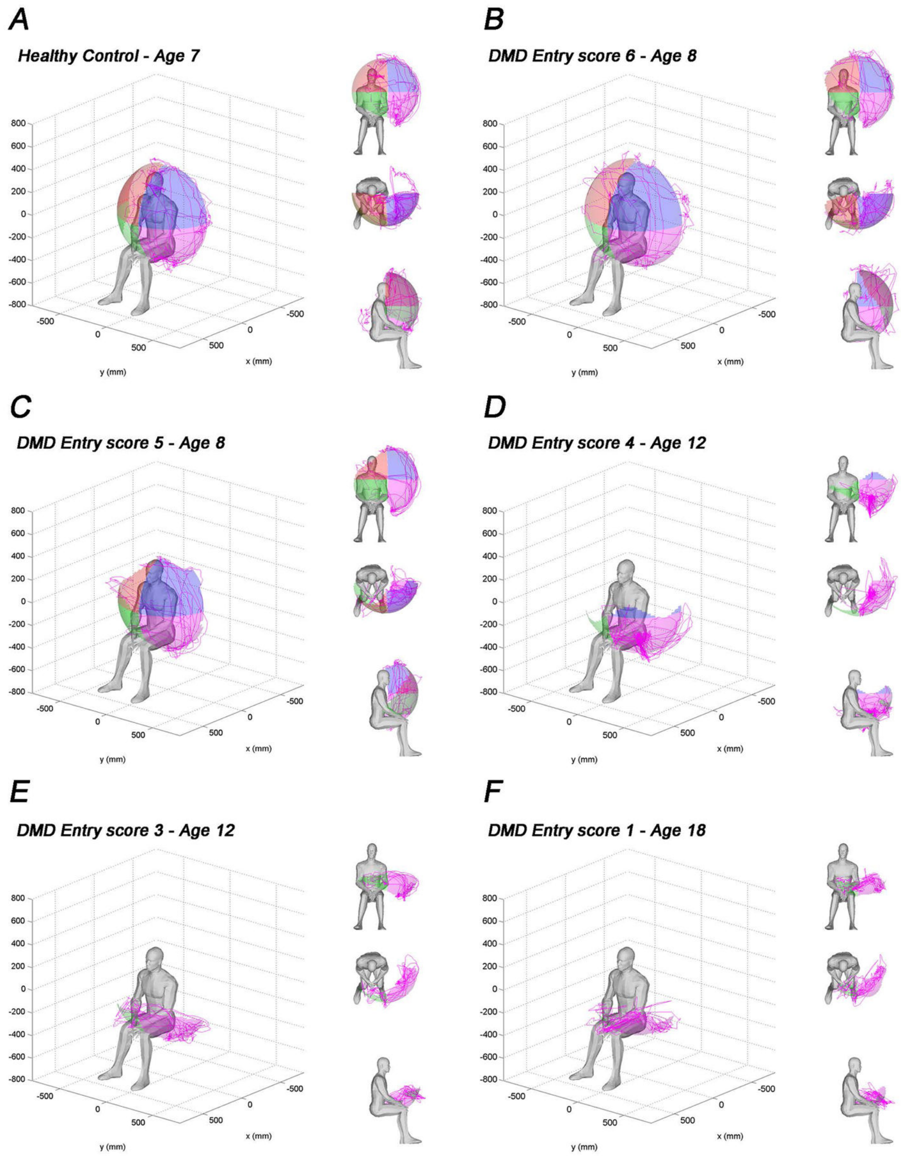

Figure 3.

Graphical visualization of 3D reachable workspace output. The representative reachable workspace output shows: (A) a 7-year old healthy control's reachable workspace viewed from different directions; also shown are reachable workspaces of individuals with DMD and progressively worsening upper extremity function as classified by the PUL entry score, total, and dimension subscores: (B) PUL entry score of 6, total: 70; shoulder: 14, middle: 33, and distal: 23; (C) PUL entry score of 5, total: 59; shoulder: 6, middle: 30, and distal: 23; (D) PUL entry score of 4; total: 55; shoulder: 3, middle: 31, and distal: 21; (E) PUL entry score of 3; total: 44; shoulder: 0, middle: 22, and distal: 22; (F) PUL entry score of 1; total: 47; shoulder: 0, middle: 25, and distal: 22.

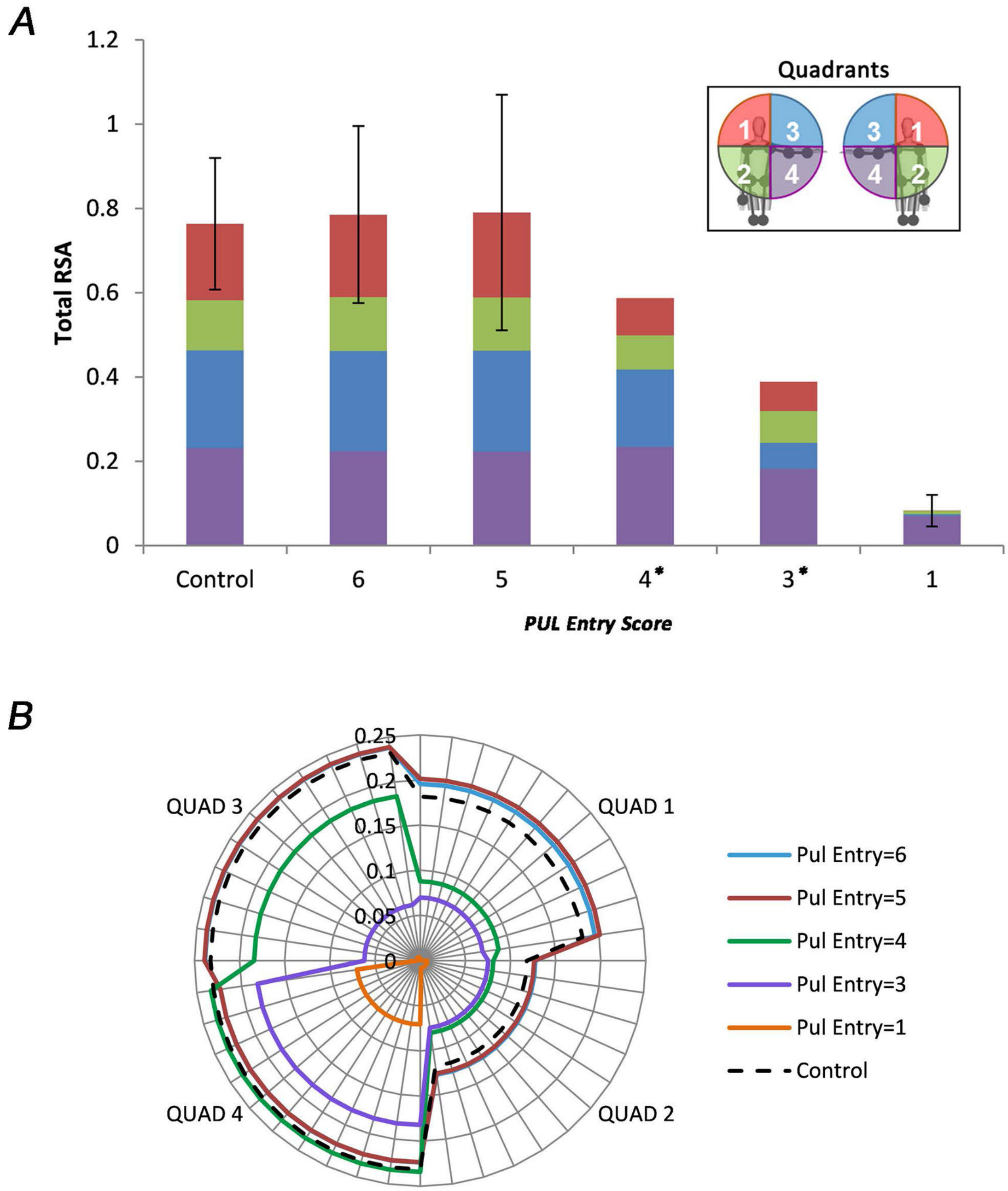

Figure 4.

(A) Bar graph showing total and quadrant RSA for both control and DMD subjects stratified by the PUL entry score. * indicates one patient under each PUL entry score, the SE is not shown for these groups. (B) Reachable workspace plot by PUL entry score (right upper extremity perspective is shown).

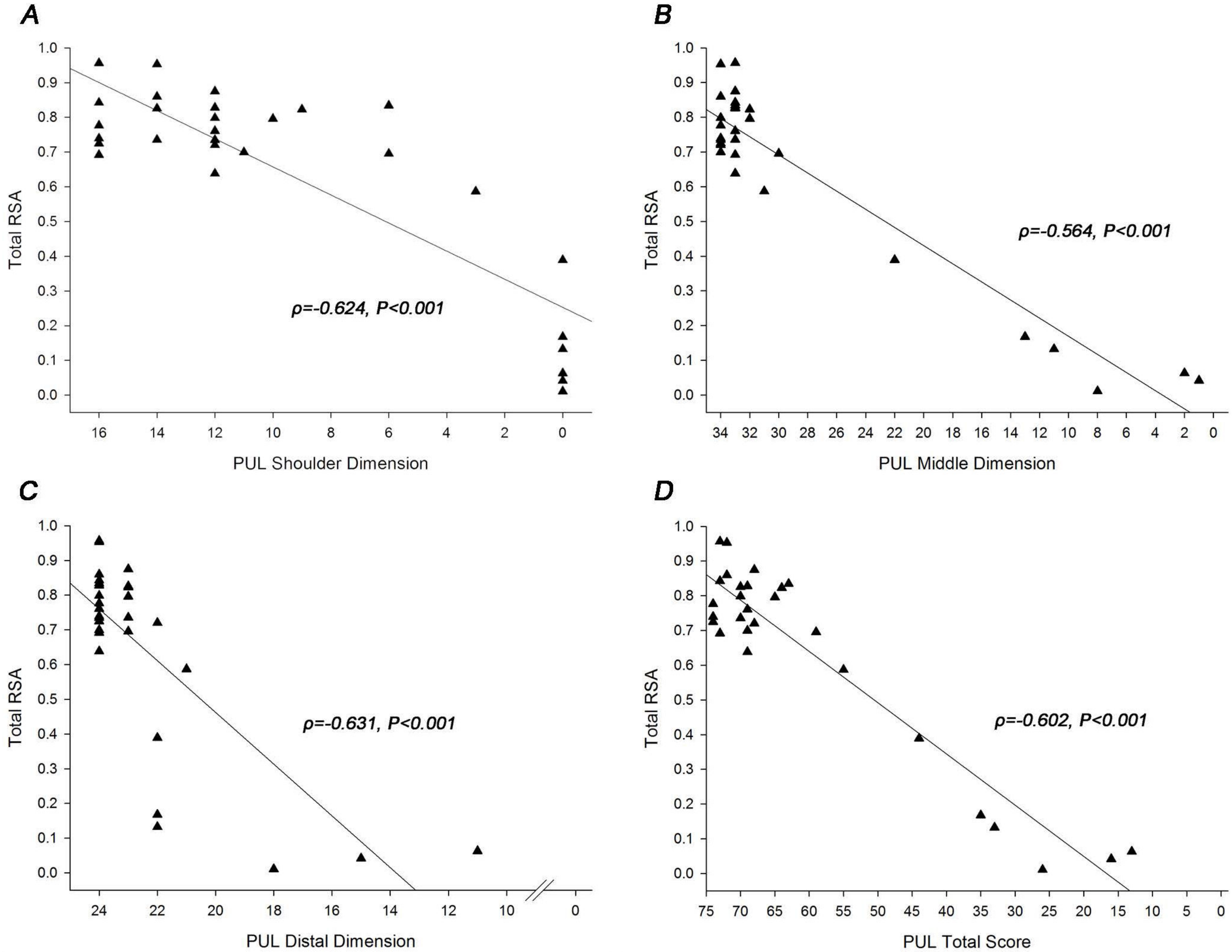

Figure 5.

Correlation between total RSA and PUL scores for the DMD cohort. Scatter plot with correlation line is shown for the total RSAs and the PUL shoulder- (A), middle- (B), and distal- (C) dimension scores, and the total PUL score (D). Respective Spearman correlation coefficients (ρ) and *P*-values are shown.

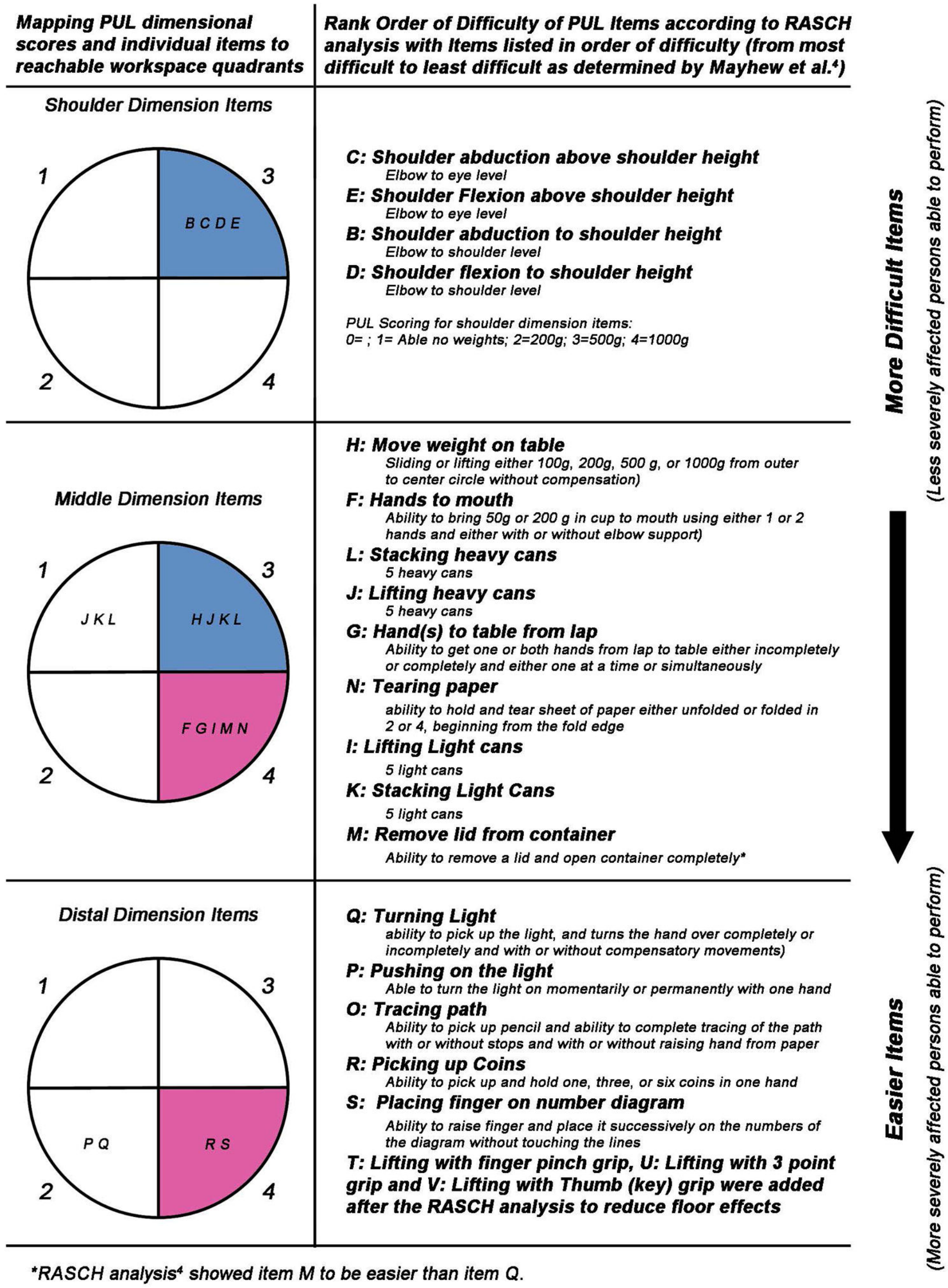

Figure 6.

Mapping PUL dimensional scores and individual questions to reachable workspace quadrants. For each PUL dimension, the quadrant that correlates most highly is colored (left upper extremity perspective is shown).

Table 1

Pearson correlation between quadrant RSA and PUL dimensional scores. The average shoulder-, middle-, and distal-dimension scores for the DMD subjects were evaluated for correlation with individual quadrant RSAs. Highest correlations are shown in bold.

		PUL		
RSA		**Shoulder (avg. score) n=29**	**Middle (avg. score) n=29**	**Distal (avg. score) n=27**
Upper	Quad 1	0.836	0.899	0.676
	Quad 3	**0.867**	**0.956**	0.700
Lower	Quad 2	0.665	0.691	0.502
	Quad 4	0.739	**0.938**	**0.800**

* All P-values are < 0.01