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Upper extremity kinematics during functional activities: Three-dimensional studies in a normal pediatric population

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Abstract

Children with brachial plexus birth palsy, burns, cerebral palsy, spinal cord injury and upper limb malformations may have diminished ability to perform activities of daily living (ADLs) due to limited upper extremity (UE) motion. Three-dimensional (3D) imaging techniques provide a way to document multi-planar functional limitations in the UE. These techniques have not been routinely used for this purpose primarily due to a lack of standardized protocols stemming from the complex nature of UE motion. Before 3D techniques can be routinely used for quantitative analysis and determination of functional limitations, standard activities and nomenclature for UE motion must be determined, and normal arm motion defined. This study establishes a normative pediatric database of 3D kinematic values during selected ADLs, enabling future comparisons with pathologic movements. Regardless of their underlying condition, children with limited UE function and ADL performance can be studied using this protocol and compared with this age-matched normal population.

Keywords: Upper extremity; 3D kinematics; Normal; Activities daily living; Motion analysis

1. Introduction

Many different conditions limit upper extremity (UE) motion in children. Children with brachial plexus birth palsy, burns, cerebral palsy, spinal cord injury and upper limb malformations may have diminished ability to perform activities of daily living (ADLs) due to pain, strength or range of motion limitations. Accurate measurement of UE movement during ADLs provides an objective measure of functional outcome and is valuable information for evaluation. Information about how healthy children perform ADLs and measurements of the UE joint angle requirements for these tasks enable the clinician to record and compare pathological UE movements with normal movements. These comparisons can help to identify compensatory strategies and functional improvement after interventions.

Three-dimensional (3D) imaging techniques allow the clinician to measure the position of the extremity in space during performance of a simulated functional task. However, these techniques have not been routinely used in the UE due to lack of standardization, resulting in part from the complex nature of UE motion [1].

For children, it is unknown what UE joint excursions are required to perform ADLs. This study uses the 3D system of analysis described by Rab et al. [2] to document UE movement in 51 normal children, aged 5–18 years, while they were performing tasks that mimic ADLs. The tasks selected simulate common self-care activities, such as grooming and personal hygiene, as well as environmental interaction. The purpose of this project was to establish normal pediatric UE kinematic values for specific ADLs so

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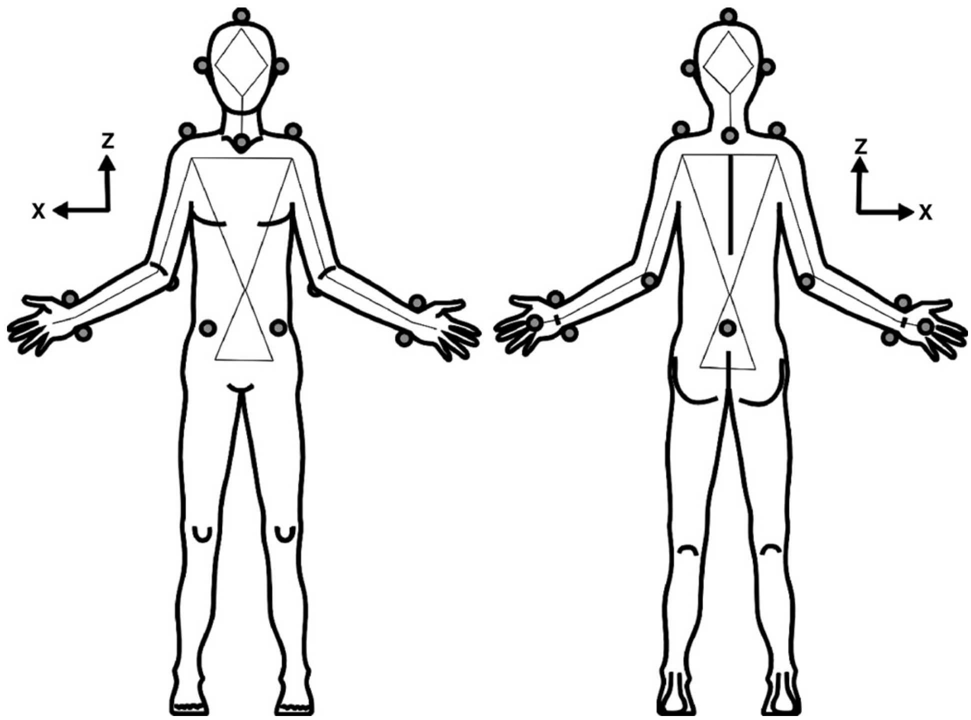

Fig. 1. Illustration of marker placement for upper extremity model.

that future comparisons with pathologic movement can be made.

2. Materials and methods

An eight camera 3D motion analysis system (Motion Analysis Corporation, Santa Rosa CA) was used to capture kinematic data at 60 Hz. Eighteen retro-reflective markers (1 in.-diameter) were attached to the child over pre-determined bony landmarks of the trunk and upper extremities where subcutaneous tissue was thin and relatively fixed to the underlying skeleton (Fig. 1; already published in Ref. [2]). A headpiece with three markers attached was placed on the subject's head. A 10 segment[1] biomechanical model was used to calculate upper extremity motion [2]. Sequential angular displacements for each joint were calculated using the sequence of flexion-abduction-external rotation. The joint motions included neck forward flexion, neck lateral flexion, neck rotation, shoulder flexion, shoulder abduction, shoulder external rotation, elbow flexion, forearm pronation, wrist dorsiflexion, wrist radial deviation, trunk forward flexion, trunk lateral flexion and trunk rotation. Shoulder motion was described by the humerus relative to the trunk, and trunk motion was calculated relative to the fixed coordinate system of the laboratory [2].

Starting position for kinematic studies was defined as standing comfortably, arms at sides, with forearms naturally rotated in a relaxed posture (pronation). Five simulated ADLs were chosen to demonstrate UE function (Table 1). Fifty-one children and adolescents, aged 5–18 years, completed the study under a protocol approved by the University of California, Davis, Institutional Review Board. Subjects had no orthopaedic or neurological conditions and no upper extremity limitations. They were asked to perform the five simulated ADLs from the start position, and to return their arm to their side after achieving the desired movement. Subjects performed the tasks at a self-selected speed, one arm at a time, with the dominant limb tested first. Joint position values were recorded during the entire movement. Unlike the study of gait, where a specific event (heel strike) allows discreet detection of the beginning and ending of an activity, UE studies have no marker of initiation or completion of a task. However, by superimposing all joint angular displacement graphs, the transition from rest to activity was easily seen and could be reproducibly identified within 2–3 frames by multiple technicians.

Table 1
Description of simulated tasks

Task name	Motion description	Functional equivalent
Back	Hand to ipsilateral back pocket	Personal hygiene
Head	Hand to top of head	Grooming
High	High reach above head	Reaching to a shelf
Receive	Forward reach to receive change	Receiving an object
Wave	Wave with arm at side, shoulder externally rotated	Waving, throwing

[1] The 10 segments are: head, neck, trunk, pelvis, left upper arm, right upper arm, left lower arm, right lower arm, left hand and right hand.

Table 2
Significant dominant vs. non-dominant limb comparisons at PTA

Task	Joint movement	Motion (°)		
		Dominant	Non-dominant	p-Value
Back ($n = 50$)	Shoulder abduction	5(9)	3(6)	.009
Head ($n = 48$)	Neck rotation	3(8)	−3(9)	.005

Mean motion values are reported with standard deviations in parentheses.

The point of task achievement (PTA) was defined as the instant when the extreme of movement necessary for the ADL was achieved. Recognition of this point from movement graphs proved simple and reliable. Joint position values were recorded during the entire movement and statistically analyzed at the PTA with the p-value set at $p < 0.01$.

Statistical tests were performed to determine differences at PTA between dominant and non-dominant limbs, specific age groups and gender. Paired t-tests were performed for all 13 joint motions for each task, comparing each subject's dominant and non-dominant arms (Table 2). Spearman rank correlation coefficients were computed between subject's age and the dominant arm's 13 joint motion values during the five ADL tasks. Post hoc analyses of variance (ANOVAS) were performed using three age groupings (5–8, 9–12 and 13–18 years) for the 13 joint measures (Table 3). These age groups were chosen based on the age appropriate surgeries that are performed for children with BPBP. T-tests for independent samples were conducted by gender and the 13 joint PTA positions during each ADL (Table 4).

Table 3
Significant age group comparisons at PTA

Task	Joint angle	Age group (years)	p-Value
Back	Neck flexion	(5–8) vs. (9–12)	.001
		(9–12) vs. (13–18)	.006
	Trunk flexion	(9–12) vs. (13–18)	<.000
Head	Neck flexion	(9–12) vs. (13–18)	.003
		(5–8) vs. (9–12)	.001
	Elbow flexion	(5–8) vs. (13–18)	<.000
		(9–12) vs. (13–18)	.006
	Arm pronation	(5–8) vs. (13–18)	<.000
High	Neck flexion	(5–8) vs. (9–12)	.004
	Elbow flexion	(5–8) vs. (13–18)	<.000
		(9–12) vs. (13–18)	<.000
	Arm pronation	(5–8) vs. (9–12)	.001[a]
	Wrist radial	(5–8) vs. (13–18)	.004
Receive	Neck flexion	(5–8) vs. (9–12)	.004
	Trunk flexion	(9–12) vs. (13–18)	.001
Wave	Neck flexion	(5–8) vs. (9–12)	<.000
		(9–12) vs. (13–18)	.001
	Trunk flexion	(9–12) vs. (13–18)	.007
	Wrist radial	(9–12) vs. (13–18)	.002

[a] Joint angle difference between age groups >10°

Table 4
Significant gender differences at PTA

Task	Joint	Motion (°)		p-Value
		Male	Female	
Back	Neck lateral flexion	−2(6)	7(8)	.000
Head	Wrist extension	−17(9)	−27(12)	.002
High	Neck rotation	−4(7)	4(10)	.004
	Trunk rotation	12(8)	5(7)	.002
Wave	Neck rotation	−2(9)	4(8)	.010

Mean motion values are reported with standard deviations in parentheses.

The positions of the UE during activities of self-care and environmental interaction were expressed as the mean PTA (Table 5). Graphic representation of joint motions were recorded in degrees (°) of angular excursion with positive values representing joint motions of flexion, abduction, external rotation and pronation, and negative values representing joint motions of extension, adduction, internal rotation and supination. A positive lateral flexion or rotation at the neck or trunk signified that the joint motion was towards the hand that was moving.

3. Results

3.1. Composite motion and ranges

Composite graphs representing joint motions during each task were normalized to task duration and include ±one standard deviation band to demonstrate the variability among the children tested (Figs. 2–4). Bar graphs represent the ranges in joint motion required for each task. The bar graphs include maximum and minimum values and ±one standard deviation band to demonstrate the variability among the children tested (Figs. 5–8). Note the PTA (not the mean) is designated by a horizontal line on the bar graphs. Data from the 9–12 age group, including both genders and both arms, are presented as composite and bar graph examples. A complete data set for the 13 joint motions (including PTA, range of motion and composite graphs) for the five ADLs for all age groupings is available upon request from the corresponding author.

3.2. Statistical tests

3.2.1. Dominant versus non-dominant limb

There were small but statistically significant differences in joint positions at PTA between dominant and non-dominant limbs for two of the simulated ADLs (Table 2). None of the statistically significant joint differences were greater than 6° of motion, therefore data from dominant and non-dominant limbs were combined for tables, composite motion curves and bar graphs.

Table 5
PTA during five simulated ADLs

Joint motion	PTA back	PTA head	PTA high	PTA receive	PTA wave
Shoulder flexion (°)	−47(11)	85(17)	142(10)	32(17)	48(27)
Shoulder abduction (°)	2(5)	36(13)	34(9)	5(10)	55(10)
Shoulder rotation (°)	−27(11)	−32(15)	−16(24)	12(21)	24(30)
Elbow flexion (°)	63(21)	110(7)	18(6)	49(25)	95(16)
Arm pronation (°)	−61(16)	−43(16)	79(25)	−55(22)	34(15)
Neck rotation (°)	−4(9)	−1(7)	−1(9)	6(9)	0(7)
Neck flexion (°)	11(10)	15(8)	12(11)	13(10)	14(9)

Joint motion reported as mean value with standard deviation in parentheses. Age group 9–12 years ($n = 28$).

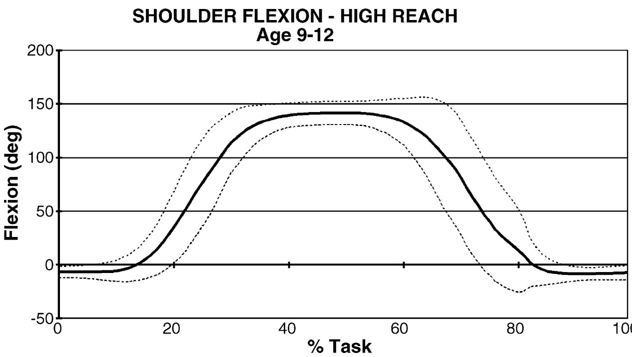

Fig. 2. Graph of shoulder flexion during the entire High task (9–12 age group). Normalized to task duration and includes ±one standard deviation band.

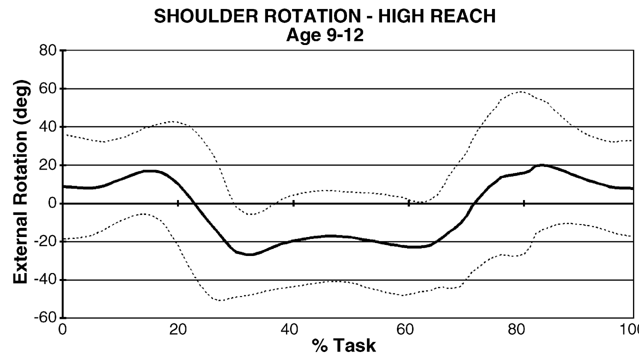

Fig. 4. Graph of shoulder rotation during the entire High task (9–12 age group). Normalized to task duration and includes ±one standard deviation band.

3.2.2. Age differences

Eight of the 65 Spearman rank correlation coefficients were significant at the alpha 0.01 level.

Post hoc ANOVAS of the PTA data showed significant differences between age groups for each of the five tasks. However, none of these differences was greater than 10° except for arm pronation during the High task, where there was a 25° difference between the 5–8 years old (mean 54°) versus the 9–12 years old (mean 79°) (Table 3). The position of forearm rotation was not standardized during this task (i.e. the child was not told to reach with the palm in any specific orientation).

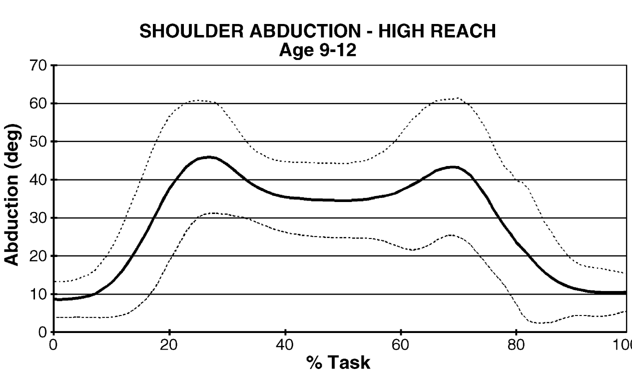

Fig. 3. Graph of shoulder abduction during the entire High task (9–12 age group). Normalized to task duration and includes ±one standard deviation band.

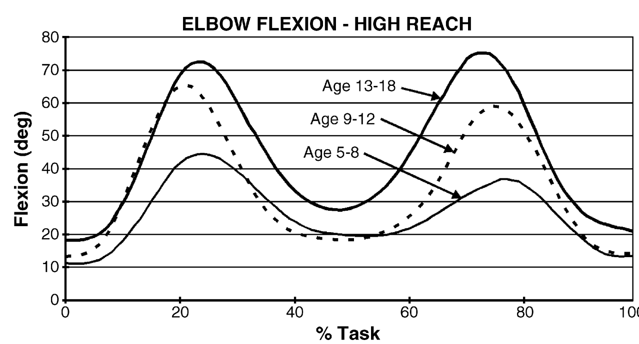

Fig. 5. Graph of elbow flexion during the High task for the three different age groups.

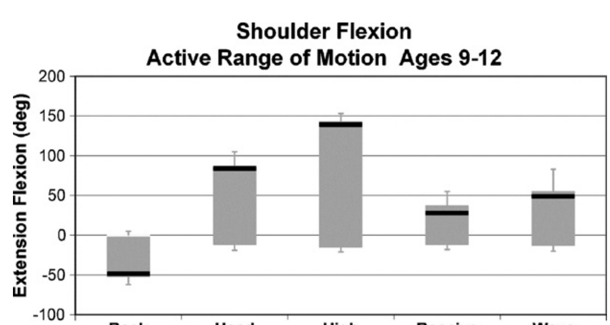

Fig. 6. Bar graph of shoulder flexion-extension active range during five tasks (9–12 age group). Includes maximum and minimum values and ±one standard deviation error bar. The mean PTA is designated by a horizontal line.

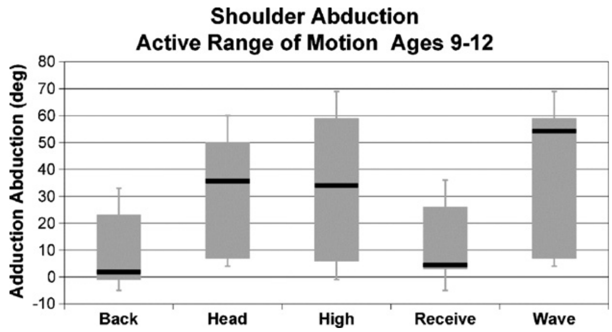

Fig. 7. Bar graph of shoulder abduction-adduction active range during five tasks (9–12 age group). Includes maximum and minimum values and ±one standard deviation error bar. The mean PTA is designated by a horizontal line.

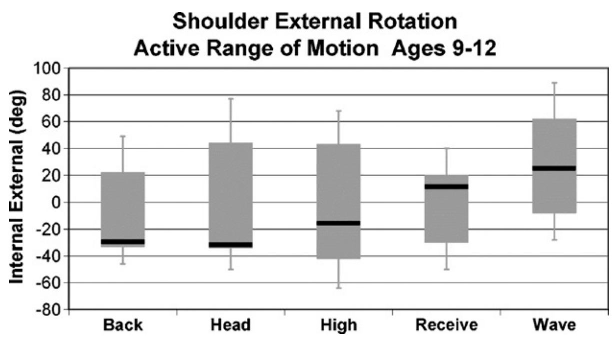

Fig. 8. Bar graph of shoulder internal-external rotation during five tasks (9–12 age group). Includes maximum and minimum values and ±one standard deviation error bar. The mean PTA is designated by a horizontal line.

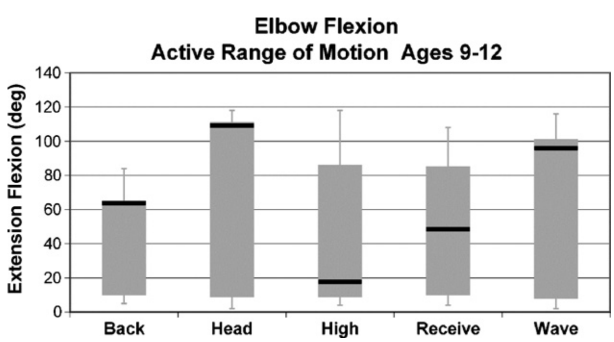

Fig. 9. Bar graph of elbow flexion-extension active range required for five tasks (9–12 age group). Includes maximum and minimum values and ±one standard deviation error bar. The mean PTA is designated by a horizontal line.

Although PTA differences were small between age groups, there were sometimes age-related differences in the arc of active movement used to achieve the PTA. An example of these age differences at the elbow during the High task are shown in Fig. 9. Because of this finding, we chose to stratify our data by age groups (5–8, 9–12 and 13–18 years).

3.2.3. Gender differences

When girls were compared with boys, small but statistically significant differences were seen for the dominant arms for four of the five simulated ADLs (Table 4). None of the statistically significant differences for gender were greater than 10°. Therefore, data from both genders were combined for composite motion curves and bar graphs.

4. Discussion

The goal of this study was to document, in children, the UE joint motion requirements to perform ADLs and to better understand how these ADLs are performed when no upper extremity pathology is present. Several unique characteristic curve patterns were seen in certain movement graphs, and some of the composite graphs representing joint motions showed a large standard deviation at the beginning and end of the task, with a tighter range of variability at the PTA. The PTA is a good position for statistical comparison of normal and abnormal subjects, or for measuring outcomes during treatment. Our observations of the PTA show that this parameter is easy to detect and is a clinically useful measure for statistical comparison of populations. It approximates clinical measurements that can be made by an observer using spatial targets, and it offers a less complex option for laboratories that are not equipped to measure kinematic history during a task.

The results of this study are influenced by methodological issues. The order used in this study entails the typical and therefore easy-to-remember clinical rotation sequence of forward flexion, abduction and rotation for data analysis and presentation [2]. The International Society of Biomechanics (ISB) has suggested a different order for reporting experimental shoulder motion [3]. Both methods are subject to instability near the regions of gimbal lock, which is a limitation of all Euler sequences. For example, the method reported here is mathematically indeterminant in shoulder joint position when the upper arm is either straight overhead or at 90° of abduction. To address the issue of shoulder joint instability near gimbal lock regions, the measurement of humeral elevation in a defined vertical plane has also been used to describe shoulder motion [4–7]. Elevation is a combination of shoulder forward flexion and abduction, between the sagittal and frontal planes, in the area where the arm is most likely to be used. However, mathematically, the measurement sequences are interchangeable and can be converted into the other.

Previous studies of the kinematics of the arm and shoulder when performing ADLs [8–10] include electrogoniometer studies of feeding and grooming. These studies reported shoulder flexion, shoulder abduction and wrist flexion of 10° or less for feeding, and 40° of shoulder flexion for grooming [8]. Studies of elbow position indicate that most ADLs are accomplished within an arc of approximately 100° of elbow flexion and forearm rotation [8–10]. These studies are technically limited by movement of the electrogoniometer from the intended axis, causing measurement error. The use of a marker tracking system reduces this problem. Magermans et al. [11] studied UE motion requirements during ADLs in healthy female adult subjects. However, shoulder motion was described as glenohumeral motion rather than motion of the humerus relative to the trunk. Due to this difference in methodology, results from this study and the present study cannot be directly compared. This highlights the need for common definitions and standardized nomenclature.

Biplanar video-recording techniques have previously been used to measure UE motion during ADLs [12–14]. The variability documented in these studies suggests that the UE is adaptive, showing the ability to perform the same tasks using different kinematic strategies [15]. The method used for this study produces estimates of joint range of motion used by normal children to achieve a specific task; however, it may be possible for a child to reach a ''normal'' PTA while using less movement range in certain joints, by following a different kinematic strategy.

Methodological differences in marker placement, UE coordinate system definitions, determining sequence order for angle computations and defining neutral joint angle positions make results from previous studies difficult to compare with the results from the present study. Our marker system is particularly sensitive to inaccuracies when the elbow is fully extended, or when marked elevation of the shoulder distorts the soft tissue over the point of the shoulder. To some extent, each marker system produces unique artifacts, and the selection of an analysis system requires a philosophical trade-off between accuracy and practicality [2]. Our normal data are therefore most useful when applied to studies of abnormal limbs using the same analytical technique.

The present study reports the functional shoulder ROM associated with each task. In some cases, these arcs of motion differ from results reported by other authors for such analogous activities as personal hygiene (Back task) and feeding (Head task) [7,8]. These differences from previous studies exist both because of the analytical method chosen and because of specific movement instructions given to subjects. In general, elbow arcs of motion needed for each task were consistent with previous studies [8–10].

The tasks selected for this study were designed to simulate common self-care requirements and do not represent the extremes of motion of the UE. Measurement of the motion requirements of the upper extremity during ADLs has several different potential clinical applications. The present study determined normal UE kinematics in children using a standardized protocol to lay the groundwork for future comparative studies. Prospective studies with pathologic populations might use this standardized protocol to compare and evaluate kinematic data relative to this established pediatric database. This UE motion analysis protocol is currently being used to study the effects of shoulder external rotation tendon transfers and humeral osteotomies in children with brachial plexus birth palsy [16] and the results of axillary contracture releases in burned children [17]. UE pathologic data can be superimposed over age matched normative curves in the same manner as pathologic gait data is superimposed over normative gait curves. With additional UE kinematic data collection, discrete variables can be determined for ADLs as specific gait data variables have been analyzed. Virtually any condition limiting UE motion and ADL performance in children could be studied using this protocol and compared with this normal population.

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