OBJECTIVE MEASURES OF MULTI-JOINT POSITION SENSE OF THE UPPER EXTREMITY: APPLICATION TO CLINICAL PAEDIATRICS

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SUMMARY
Multi-joint position sense of the upper extremity was evaluated in 103 children and adolescents, 5 to 18 years old, using the KINARM Exoskeleton robot. Subjects completed an arm position matching task in which the robot passively moved one arm to one of nine spatial positions and subjects were instructed to actively match the position with their opposite arm. Linear regression models were used to identify significant (P<0.01) effects of chronological age on three measures of multi-joint position sense: (1) trial-to-trial variability in end-point position, (2) the ratio between spatial areas covered by the passive and active arms, spatial contractions/expansion, which provides a measure of spatial perception, and (3) systematic shifts, or errors, in matching. With increasing age, trial-to-trial variability decreased and spatial contraction/expansion ratio normalized towards a one to one ratio, indicative of improvements in spatial perception of limb position. Systematic shifts in position matching were constant across all developmental ages. Our results provide a robust profile of the development of multi-joint position sense of the upper extremity. This profile will be useful for evaluating the performance of children with disabilities.

INTRODUCTION
The contribution of sensory impairments to the observed motor coordination deficits in children with developmental disabilities is increasingly being recognized [1]. As an example, accurate limb position-sense has been shown to be essential to the successful planning and coordination of functional activities that engage the upper extremities in asymmetrical fashion, such as using a knife and fork. Research on the sensory component of motor control in children has, to date, largely focused on the accuracy of perceiving direction and velocity of displacements of single joints, as well as the accuracy in matching angular positions, again at single joints [2,3,4]. More recent evidence, however, indicates that accuracy in matching hand positions in space is significantly influenced by the position of the shoulder joint, emphasizing the importance of considering multi-joint position sense in the evaluation of clinical populations [5].

The goal of this study was to use the KINARM Exoskeleton robot (BKIn Technologies Ltd, Kingston, Ontario, Canada) to profile the development of multi-joint position sense of the upper extremity in children and adolescents, 5 to 18 years old.

METHODS
All methods and procedures for this study received ethical approval from the Queen’s University and Affiliated Hospitals Research Ethics Board. The KINARM is a bilateral robotic device in which upper arm, forearm and hand fit snugly into troughs that provide gravitational support during planar arm movements, without assisting movement in any way. Each exoskeleton is fully adjustable permitting them to precisely follow arm movements, independent of the direction and magnitude of shoulder and elbow joint motions. Encoders attached to the motors indirectly measure the angular position of the shoulder and elbow joints, and these positions are used to calculate the linear position of the hand in the external workspace.

Multi-joint position sense of the upper extremity was evaluated using a position-matching task. The robot passively moved one of the subject’s arms to one of nine spatial positions, and subjects were instructed to actively match the position with the opposite arm. Passive displacements were made along a linear path, using a bell-shaped speed profile with a maximum speed of less than 1 m/s; each spatial position required different combinations of shoulder and elbow joint positions. In each evaluation session, all spatial locations were visited once per trial block, in pseudo-random order, and six blocks were completed for each arm. Performance was quantified by three outcome measures: (1) trial-to-trial variability in end-point position, (2) the ratio between spatial areas covered by the passive and active arms, spatial contractions/expansion, which provides a measure of spatial perception, and (3) systematic shifts, or errors, in matching. A complete description of the calculation of the measured outcomes is provided in Dukelow et al [6].

Multi-joint position sense was evaluated in 103 children, 49 males and 54 females, 5 to 18 years old, with no history of developmental, neurological, cognitive or behavioural disorders. Hand dominance was determined using the modified Edinburgh Handedness Inventory [7]. Linear regression models were constructed from the cross-sectional data by plotting the mean individual scores for each measure, collapsed across the nine spatial positions, as a function of chronological age (CA). For measures showing significant effects of gender or handedness (Kolmogorov-Smirnov tests, P< 0.01), separate models were constructed for each subgroup. Linear regression analysis was subsequently used to assess whether each measure was significantly influenced by CA (F-tests, P< 0.01). Finally, residuals were computed for each measure by subtracting out the slope and intercept (P< 0.01) or the mean (P≥ 0.01) and were used to calculate percentiles scores (1, 2.5, 5, 25, 50, 75, 95, 97.5, 99).

RESULTS AND DISCUSSION
The regression models and 97.5% confidence interval for the three outcome measures are shown in Figure 1; the corresponding model parameters and percentiles are reported in Table 1. While between-subject variability was high for each of the three measured outcomes, significant age-dependent effects were observed (P< 0.01). With increasing age, trial-to-trial variability decreased and spatial contraction/ expansion ratio normalized towards a one to one ratio, indicative of improvements in spatial perception of limb...
position. Systematic shifts in position matching were constant across all developmental ages. No effects of sex and handedness were identified.

**Figure 1:** Linear regression model for the 3 measures of multi-joint position sense: trial-to-trial variability (Var\(_xy\)), spatial contraction/expansion (Area\(_xy\)), and systematic shifts (Shift\(_xy\)). The regression line (thick line) and 97.5% confidence limits (thin lines) are shown.

The precise measurement provided by the KINARM exoskeleton discriminated age-dependent differences in the spatial perception of limb position from systematic errors that have been documented in adult populations with a stroke [6]. The KINARM, therefore, promises to be a reliable clinical and research tool for the evaluation and clinical management of impairments in sensory-motor coordination of children with developmental disabilities.

**CONCLUSIONS**
Our results provide a robust profile of the development of multi-joint position sense of the upper extremity. This profile will be useful for evaluating the performance of children with disabilities and to assess the effectiveness of clinical intervention aiming to improve sensory processing for motor control.

**ACKNOWLEDGEMENTS**
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**Table 1:** Model parameters and percentiles for measures of matching performance (n=103 subjects; 49 males and 54 females)

<table>
<thead>
<tr>
<th>Group</th>
<th>Measure</th>
<th>Transform</th>
<th>Model Fit Slope</th>
<th>Model Fit Bias</th>
<th>Percentiles 1</th>
<th>Percentiles 2.5</th>
<th>Percentiles 5</th>
<th>Percentiles 25</th>
<th>Percentiles 50</th>
<th>Percentiles 75</th>
<th>Percentiles 95</th>
<th>Percentiles 97.5</th>
<th>Percentiles 99</th>
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<tr>
<td>All</td>
<td>Var (cm)</td>
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<td>1.403</td>
<td>-0.550</td>
<td>-0.497</td>
<td>-0.465</td>
<td>-0.201</td>
<td>-0.001</td>
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<td></td>
<td>Cont/Exp</td>
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<td>0.324</td>
<td>-0.530</td>
<td>-0.463</td>
<td>-0.463</td>
<td>-0.204</td>
<td>-0.040</td>
<td>0.169</td>
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<td>0.738</td>
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<td>0.517</td>
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<td>7.981</td>
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<td>11.627</td>
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Abbreviations: Var, inter-variability; Cont/Ext, spatial contraction/expansion.

**REFERENCES**