Measuring kinaesthetic sensitivity in typically developing children

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This study presents a method to quantify a child's sensitivity to passive limb motion, which is an important aspect of kinaesthesia not easily examined clinically. Psychophysical detection thresholds to passive forearm motion were determined in a group of 20 typically developing pre-adolescent children (mean age 12y 6mo, SD 10mo, range 11–13y) and a group of 10 healthy adults (mean age 29y 10mo, SD 10y 7mo, range 18–50y). A newly designed passive motion apparatus was used to measure the time to detection of forearm motion and the errors in determining movement direction. Results showed that limb motion sensitivity became increasingly variable below 0.3°/s in children and adults. In comparison with adults, movement detection times in the pediatric group were increased by between 4 and 108% for the range of tested velocities (0.075–1.35°/s). At 0.075°/s, 5% of the children, but 50% of the adults, made no directional error, indicating that motion perception became unreliable at such low velocity in both groups. The findings demonstrate that sensitivity to passive forearm motion in children should be tested at a range between 0.075 and 0.3°/s. They further suggest that passive motion sensitivity may not be fully developed in pre-adolescent children.

Kinaesthesia is the conscious awareness of limb position or limb motion. In general, one distinguishes between an active motion and a passive motion sense, depending on whether the limb is moved by a force internal or external to the mover.[1–3] Kinaesthetic perception is based on signals from peripheral proprioceptive receptors, such as muscle spindles or Golgi tendon organs. Several childhood motor disorders are believed to be linked to abnormal kinaesthesia. For example, children diagnosed with developmental coordination disorder may show reduced kinaesthetic acuity in conjunction with visual and visuomotor deficits.[4–7] (Here, 'acuity' refers to the sharpness or resolution of the kinaesthetic system.)

Much of the work examining kinaesthetic sensitivity during child development has relied on the Kinaesthetic Sensitivity Test.[8–12] (The term 'sensitivity' refers to the minimal physical stimulus eliciting a kinaesthetic perception.) The Kinaesthetic Acuity component of the test requires participants to differentiate the position of the left and right arm after one arm has been passively moved by the experimenter. The Kinaesthetic Acuity component tests the acuity of the limb position sense, but provides no data about passive or active motion sense, which are two other important components of kinaesthesia. This methodology has also been criticized both for its accuracy[13] and for its ecological validity.[14]

Kinaesthetic sensitivity is not easily assessed in children, because of their limited attention span and because proprioceptive testing requires focusing on a sensory modality that is typically not at the center of a child's attention. In addition, the testing must be easily understood by the child and simple to administer, and should produce objective measures for subsequent clinical evaluation.[12] With these requirements in mind, an apparatus and testing paradigm was designed to assess the sensitivity of humans to detect passive forearm motion. The paradigm does not rely on

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the comparison of limb positions, but rather investigates the sensitivity of a single limb to passive movement. The testing apparatus and paradigm overcome the limitations of measurement techniques based on limb position matching and can also be used to compare kinaesthetic acuity between limbs. The device was successfully employed to determine passive motion thresholds in patients with Parkinson disease, revealing elevated motion detection thresholds in these patients.[15] The current study sought to examine the viability of this method for assessing passive motion sensitivity in a group of typically developing pre-adolescent children by measuring the time-to-detection and each individual's ability to detect the direction of the movement. The goals of the study were to demonstrate that the method can provide measures of limb motion sensitivity in children and to determine at what range of limb velocities kinaesthetic perception becomes unreliable in pre-adolescent children. Such knowledge allows future test protocols to narrow the range of testing velocities, which, in turn, will shorten testing so that it can become suitable for clinical application.

METHOD

Participants

Twenty children ranging in age from 11 to 13 years (10 females, mean age 12y 8mo, SD 10mo; 10 males, mean age 12y 4mo, SD 10mo) and 10 adults ranging in age from 18 to 50 years (five males, five females, mean age 29y 10mo, SD 10y 7mo) participated in the study. For pediatric participants voluntary written consent was given by a parent, while the children gave voluntary written assent. Adult participants gave voluntary written consent. The experiment was approved by the institutional review board of the University of Minnesota.

All participants had no reported history of upper limb injury that could have impaired peripheral neural transmission of proprioceptive signals. All children were screened for abnormal and delayed motor development using a questionnaire completed by the parent. If questionnaire information indicated atypical motor development, the individual was excluded from the study. Based on the questionnaire results one child with a slight delay in motor development was excluded from the study. The Edinburgh Handedness Inventory was completed to determine hand dominance.

Instruments and procedures

Simple reaction time task

In order to account for the variable reaction times of each individual participant, an auditory reaction time test was administered before the beginning of the passive motion testing. Reaction time data were collected using a digital data acquisition system (Biopac Inc., Goleta, USA). Participants wore headphones and held a trigger in their non-dominant hand. They were instructed to press the trigger as soon as they heard an auditory stimulus. Ten stimuli were generated at random inter-stimulus intervals. An average reaction time for each individual was calculated by computing the mean of the 10 recorded reaction times.

Passive motion sensitivity task

The passive motion apparatus consisted of a 0.61×0.1m aluminium splint that could rotate horizontally (transverse plane) at one end. The top portion of the splint was covered with soft foam material for comfort and to minimize tactile cues (Fig. 1). The pivot end of the device was supported by a 0.36m long metal drive shaft connected to the bottom of the splint at a distance of 0.025m to a support beam on the base of the device. Motion of the apparatus was produced by means of a five-phase stepping motor (precision: 5466 steps per 1°=0.00018°/step; Nyden Inc., San Jose, USA). The desired angular velocity of the apparatus was specified via a digital potentiometer. A digital LED display on the control interface showed the number of steps taken by the motor during any movement. Movement direction was specified via a toggle switch. Pressing a

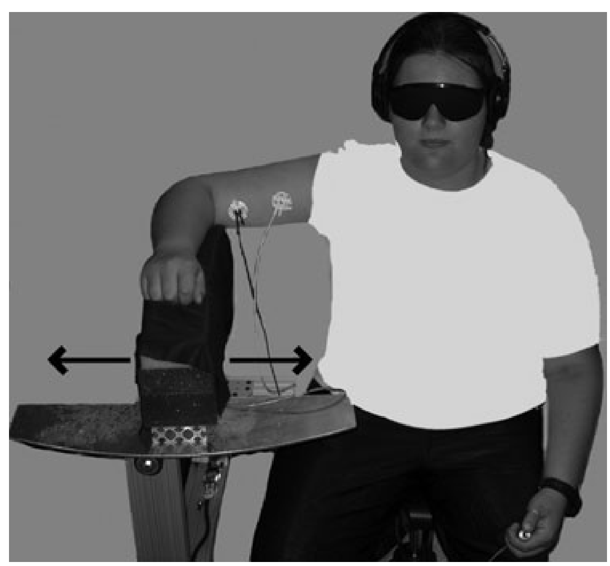

Figure 1: Experimental setup. Participants were seated in a position that allowed their dominant arm to rest on the splint with their shoulder at an angle of less than 90° of horizontal abduction. They held a triggering device in their non-dominant hand to stop the motion of the sled. Electromyography was used to monitor activity in the forearm extensor and flexor muscles. The arrows indicate the direction of the testing apparatus.

handheld trigger device interrupted current flow to the motor and stopped splint motion.

Participants were seated on a stool parallel to the apparatus with their forearm completely at rest on the splint. Stool height was adjusted to achieve a 'comfortable position' of 70 to 85° shoulder abduction. The trigger was placed in the individual's non-dominant hand. The axis of rotation of the elbow was aligned directly above the pivot shaft of the apparatus, allowing rotation of the splint to cause either a flexion or extension movement of the forearm in the transverse plane. The forearm was positioned on the splint to begin testing at 90° elbow flexion confirmed by a handheld goniometer. To occlude vision, participants wore opaque goggles. Extraneous sounds were masked by headphones (Fig. 1).

The experimenter initiated each trial with a verbal precue to direct the participant's attention. Then the splint began to move at a preset velocity. Participants pressed the trigger as soon as they detected forearm motion. Splint motion ceased and participants orally indicated the direction of forearm motion as either 'toward' the body or 'away' from the body.

The experiment consisted of 48 pseudo-randomly presented trials in the pre-adolescent group and 72 total trials for the adults. Pilot testing had shown that in excess of 50 trials some children lost their attention and gave erratic responses. Adults with their greater attention span would go through an extended protocol which provided a larger sample. Motion sensitivity was tested at the following 10 fixed angular velocities of the apparatus: 0.075°/s, 0.15°/s, 0.30°/s, 0.45°/s, 0.6°/s, 0.75°/s, 0.9°/s, 1.05°/s, 1.2°/s, 1.35°/s. All participants were informed that the splint would move during each trial and that the procedure would not trick them into giving a false answer. At the beginning of testing, all participants performed test trials at 1.5°/s and 1.65°/s to become familiar with the apparatus and the procedure. These test trials were not included in the later analysis. The children experienced each of the 10 velocities four times (two flexion and two extension trials), whereas adults experienced six trials (three flexion and three extension trials) at each velocity. Velocity settings varied randomly between flexion and extension and were presented in both ascending and descending order to account for any possible order effect. All participants were given a 10 minute break after completion of the reaction time test and a 20 minute break after the first half of the trials.

Surface electromyography (EMG) was recorded for the biceps and triceps muscles of the tested arm at a sampling frequency of 200Hz using standard silver–silver chloride electrodes. Online monitoring of the EMG was used to assure motion detection was passive and not compromised by active muscle innervation. Trials revealing muscle activity were excluded from data analysis and repeated at the end of the testing protocol.

Measurements

Directional error

For each trial the participant's judgment of movement direction and the actual direction of the splint were recorded. Directional error was defined as the percentage of incorrect responses for each velocity.

Movement detection time

The number of steps taken by the motor before the participant pressed the trigger was recorded for each trial. Dividing the total number of steps taken by the set velocity of the apparatus (specified in steps/s) yielded total detection time. To account for differences in reaction time each individual's mean reaction time was subtracted from the total detection time to obtain an unbiased measure of the time between movement initiation and detection (adjusted detection time): adjusted detection time = detection time – mean reaction time.

Statistical analysis

The reaction time and directional error data followed a normal distribution and group comparisons were performed using independent *t*-tests with a level of significance set at p=0.05 (two-tailed). On the basis of Shapiro–Wilk tests, the assumption of normality was not reasonably met for the movement detection time data at all velocity conditions. Therefore, Mann–Whitney *U* tests were performed to determine group differences in adjusted detection time.

Psychophysical sensitivity function

Based on the median detection time for each individual at each tested velocity an exponential decay function was fitted to determine passive motion sensitivity of each group across the range of tested velocities. The sensitivity function had the following form: $\mathrm{ADT} = a \times e^{(-\omega/b)} + y_0$, where 'ADT' is the median adjusted detection time, 'ω' is the angular velocity in °/s, 'a', 'b', and 'y_0' are constants to be estimated, and 'e' refers to Euler's number.

RESULTS

Reaction time measurements

The adult group had a significantly faster mean reaction time, at 214m/s (SD 42.5), than the pediatric group at 260m/s (SD 42.8; p=0.009).

Errors in perceiving the direction of passive motion

Incorrect judgments of movement direction (i.e. indicating flexion when the arm was extended or vice versa) occurred

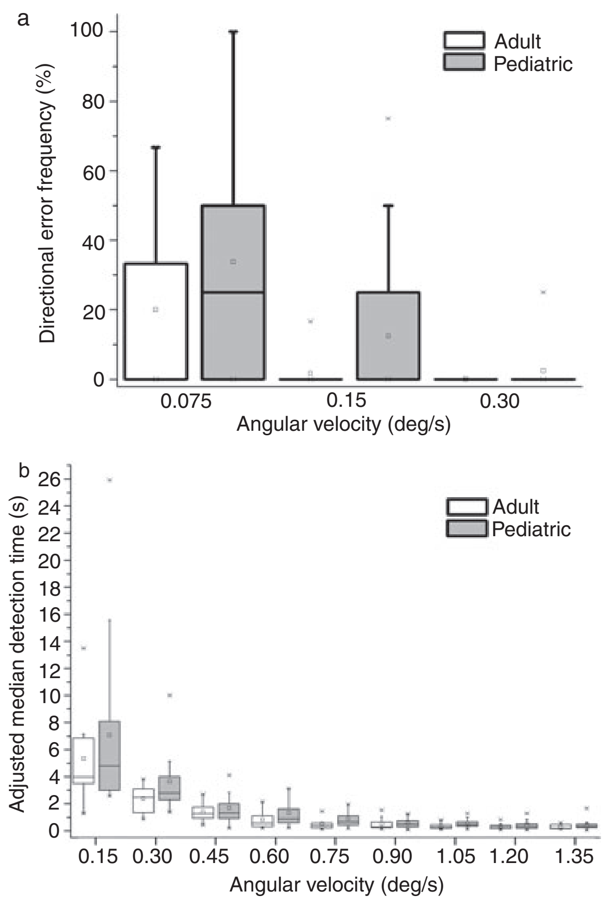

Figure 2: (a) Frequency of errors in movement direction. Percentage of trials at each of the three slowest tested velocities which resulted in an error in the directional judgment of the forearm movement (flexion or extension). The small square within each box represents the mean and the line through the box the median. Top and bottom of the box mark the 25th and 75th quartiles respectively. Whiskers indicate the 5th and the 95th centile. (b) Adjusted detection time: comparison of the adult and pediatric group.

only during trials with angular velocities of 0.30°/s or below in both the adult and pediatric group (Fig. 2a).

At the slowest angular velocity of 0.075°/s, five out of 10 adults were always accurate in judging direction, whereas only one child achieved perfect accuracy (i.e. 100% correct response rate). Four adults and eight children did not achieve a 75% correct response rate at this velocity. For the second slowest velocity (0.15°/s), one adult made a single error during the six trials. In contrast, seven children committed errors, with two children not reaching the 75% accuracy level. At angular velocities of 0.30°/s or above all adults were correct in 100% of the trials, whereas all children were correct in at least 75% of the trials. Comparing mean directional error for the three lowest velocities yielded no statistically significant difference between the adult and pediatric group (p>0.05).

Movement detection times

Because of the high frequency of accuracy errors at the 0.075°/s angular velocity, detection times were analysed only for trials at the 0.15°/s angular velocity and above. For both the adults and children the detection times increased exponentially as the angular velocity of their forearm decreased (Fig. 2b). This trend continued through the trials at the 0.75°/s angular velocity. Velocities above 0.75°/s revealed only small changes in median detection times. Table I lists the median ADT values for adults and children at each of the 10 tested velocities. With respect to the adult group median, ADT values were consistently higher in the pediatric group over all tested velocities, ranging between 4 and 108% longer than adult levels. However, given the limited sample size, these differences yielded statistical significance only for the 0.75°/s velocity (p=0.03; all other p values >0.05).

Passive motion sensitivity

For the adult and pediatric groups psychophysical sensitivity functions were fitted on the basis of the median ADT values for all velocities of 0.15°/s and above (Fig. 3). The coefficients of determination (R^2) for the two obtained functions were 0.999 and 0.984 for the pediatric and adult groups respectively, indicating a high goodness of fit of each model function. The estimated model parameters are specified in Figure 3. The sensitivity function for the pediatric group was elevated compared with that of the adult group. This reflects the larger median ADT values of the pediatric group at all limb velocities.

DISCUSSION

Most clinical examinations and neuropsychological tests examine the limb position sense when assessing kinaesthetic function. The perception of limb motion (active and passive motion sense) is usually not tested because no standardized protocol or equipment is currently available. The primary purpose of this study was to demonstrate a tool and paradigm for the accurate assessment of detection thresholds for passive limb motion that may be suitable for testing children. The methodology examines a single limb and does not rely on comparing or matching the position of separate limbs. Thus, perceptual judgments are not confounded by additional cognitive processes' requiring working memory or by immature motor control processes.

Here we present data on the acuity of the passive limb motion sense in a small sample of typically developing pre-adolescent children and healthy adults. In order for this testing method to be applicable in a clinical setting, the

Table I: Median adjusted detection times (s) for the adult and pediatric groups

	Angular velocity (°/s)								
	0.15	0.30	0.45	0.60	0.75	0.90	1.05	1.20	1.35
Adults	4.02	2.63	1.34	0.58	0.38	0.27	0.25	0.28	0.17
Children	4.92	2.87	1.39	0.99	0.79	0.50	0.44	0.33	0.34
Difference from adults (%)	+22.4%	+9.1%	+3.7%	+70.7%	+107.9%	+85.2%	+76.0%	+17.9%	+100.0%

Each value represents the group median adjusted detection time for each tested velocity. The bottom row indicates how much longer the children's median detection times were than those of the adult group.

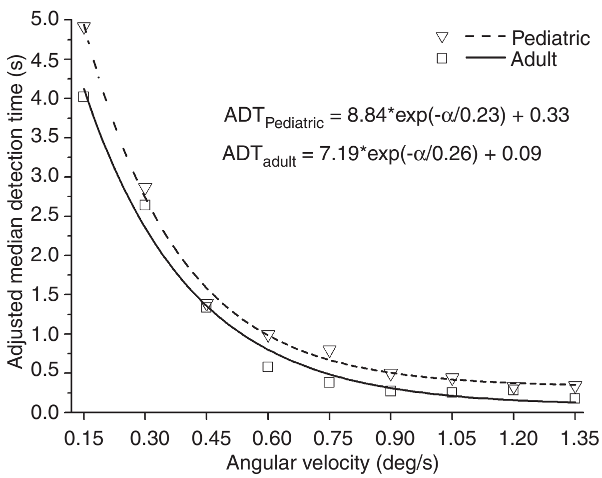

Figure 3: Psychophysical sensitivity functions for each group based on the median adjusted detection times (ADT) values of each group. The equations indicate the estimated parameters of each function. Units are seconds. α=angular velocity (deg/s)

method must be sensitive enough to discern individual differences among healthy children and to express their kinaesthetic acuity with respect to healthy adults (Fig. 3). We previously demonstrated that this method was sensitive enough to identify impaired passive motion sense in patients with Parkinson disease who were at an early stage of their disease.[15] On the basis of the data presented in this study and in our previous work, the paradigm seems promising in assessing the kinaesthetic acuity in pediatric populations with suspected soft neurological signs of central origin.

Judging the direction of passive motion

For velocities over 0.30°/s all children and adults identified the direction of motion without error. This information about the range of detection thresholds in pre-adolescent populations is helpful for the design of future test protocols, because the identification of perceptual limits can lead to significantly shorter testing times without invalidating the test results. It also implies that perceptual differences become magnified and more apparent at passive motion velocities below 0.30°/s. Differences in directional errors among children became most pronounced at the two slowest tested velocities (0.075 and 0.15°/s). This also implies that future test devices need to be able to produce angular velocities below 0.075°/s in order to capture detection thresholds reliably.

Passive motion sensitivity

On the basis of the detection time data, sensitivity functions were fitted for each group. They revealed that the passive limb motion sensitivity function for the pre-adolescent children was comparable to that of the adults, although as a group the children had consistently longer detection times than adults. Median detection times of the pediatric group were up to 108% longer than those of the adults, indicating that some typically developing pre-adolescent children may still show lower sensitivity than adults. However, before detection time values can be used to compare the kinaesthetic sensitivity of pediatric populations displaying atypical motor development with that of a typically developed cohort, a comprehensive study with a larger age range and a larger sample population is imperative.

In summary, these findings demonstrate that, first, it is feasible to measure passive motion sensitivity in pre-adolescent children to obtain a quantifiable measure of their kinaesthetic sensitivity. Second, the method presented here does not rely on matching limb positions, thus allowing for determination of side differences (i.e. left vs right arm). The paradigm is suitable for testing both healthy and pediatric populations with atypical motor development. The data from this study provide the first information about the velocities at which the differences in limb motion perception become most prominent. This knowledge will be important when designing standardized clinical protocols. Third, this method eliminated the effect of gravity on detecting limb motion. Moving against gravity will very likely yield different sensitivity functions because of the additional cues derived from mechanoreceptors. Fourth, our findings suggest that passive motion sensitivity has not necessarily reached adult levels in pre-adolescent children.

STUDY LIMITATIONS AND OUTLOOK

The scope of this study was necessarily limited given the small sample size of the pediatric group (*n*=20). A post-hoc power analysis of the detection error data at the 0.03°/s setting showed an effect size of 0.72. With this effect size a sample size of 34 would be necessary to achieve α=0.10. This implies that testing a larger sample size is necessary before a complete set of normative data from healthy children can be established.

In contrast to previous methods for testing kinaesthetic sensitivity in children, the method presented allows a bilateral comparison of proprioceptive thresholds across limbs, which is helpful for detecting differences in the kinaesthetic function when hemispheric differences are expected (e.g. because of peripheral or central nervous system damage). The test method is not restricted to measuring passive motion sensitivity of the forearm but has the potential to be applied to other joints, although this would require the design of appropriate passive motion devices.

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