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Age-Related Differences in the Motor Planning of a Lower Leg Target Matching Task

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Abstract

While the development and execution of upper extremity motor plans have been well explored, little is known about how individuals plan and execute rapid, goal-directed motor tasks with the lower extremities. Furthermore, the amount of time needed to integrate the proper amount of visual and proprioceptive feedback before being able to accurately execute a goal-directed movement is not well understood; especially in children. Therefore, the purpose of this study was to initially interrogate how the amount of motor planning time provided to a child before movement execution may influence the preparation and execution of a lower leg goal-directed movement. The results displayed that the amount of pre-movement motor planning time provided may influence the reaction time and accuracy of a goal directed leg movement. All subjects in the study had longer reaction times and less accurate movements when no pre-movement motor planning time was provided. In addition, the children had slower reaction times, slower movements, and less accurate movements than the adults for all the presented targets and motor planning times. These results highlight that children may require more time to successfully plan a goal directed movement with the lower extremity. This suggests that children may potentially have less robust internal models than adults for these types of motor skills.

Keywords

Internal Model; Motor Development; Children; Action Planning

1. Introduction

Motor actions are highly dependent upon the formulation of a motor plan that is based on a feed-forward or a feedback control strategy. Feed-forward control is based upon an internal model, which is used to predict the outcomes of the motor command being formed; while feedback control uses errors between the internal model and the actual movement trajectory to make online corrections (Mussa-Ivaldi, 1999; Shadmehr & Mussa-Ivaldi, 1994). An

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internal model is formed by integrating information about the current position and velocity of a limb in space, and can be specified based on the current sensory feedback as well as past experiences (Mussa-Ivaldi, 1999). Proper integration of this information will allow an individual to more accurately control their movement and successfully complete the movement to achieve the desired outcome. Since the environments in which motor tasks are performed are ever changing, an internal model must be robust and adaptable to these changes. Humans are relatively skilled at adapting their internal models based on these ever changing environments. For example, adaptation of an internal model has been seen to occur rather quickly following the implementation of a force field or visuomotor transformation during goal-directed reaching tasks (Contreras-Vidal, 2006; Contreras-Vidal, Bo, Boudreau, & Clark, 2005; Ghez et al., 1997; Jansen-Osmann, Richter, Konczak, & Kalveram, 2002; Shadmehar & Mussa-Ivaldi, 1994; Takahashi et al., 2003). The adaptation of the internal model can be seen by an increase in errors when the applied force field or visuomotor transformation is removed, indicating that the internal model has correctly adapted to the preceding environmental dynamics.

The level of preparation of the internal model is dependent upon the amount and type of information provided before movement execution and the time provided to process this information (Pellizzer, Hedges, & Villanueva, 2006). In feed-forward or goal-directed motor tasks, the information provided to an individual before motor execution can be manipulated by altering the visual information about the limb's initial location or the position of the target (Pellizzer & Hedges, 2004; Shadmehar & Mussa-Ivaldi, 1994). Furthermore, the amount of time the visual information about the target location is provided to an individual can be altered in order to provide either no processing time or ample processing time (Pellizzer et al., 2006). By quantifying the reaction time, movement time, and accuracy for a goal-directed motor task, one may interrogate the level of preparation and integration of sensory information. Increased reaction and movement times suggest that an individual takes longer to integrate the sensory information, and decreased accuracy suggests that an improper feedforward internal model was selected for the desired movement outcomes. Therefore, the proper integration of sensory information is vital for proper planning of motor actions.

The robustness of an internal model is also dependent upon the amount of previous experience utilizing and adapting the internal model to meet specific task demands (Lukos, Choi, & Santello, 2013; Mussa-Ivaldi, 1999). For example, highly skilled athletes with extensive motor experience, such as elite soccer players, display higher levels of accuracy than non-athletes when faced with changes in task demands such as end point trajectory placement or a moving soccer ball to kick (Egan, Verheul, & Savelsbergh, 2007; Ford, Hodges, Huys, & Williams, 2009). These athletes also display faster reactions times suggesting that they are able to integrate the appropriate sensory cues for a movement and predict the consequences of their results than non-athletes potentially due to extensive experience performing and adapting highly specific action patterns (Montes-Mico, Bueno, Candel, & Pons, 2000; Romeas & Faubert, 2015; Vantinen, Blomqvist, Luhtanen, & Hakkinen, 2010). Therefore, the amount of preparation before a goal-directed movement is highly dependent upon an individual not only being provided with adequate information

concerning limb dynamics and goal of the motor task, but also on the robustness and adaptability of the internal model underlying the motor skill.

It is commonly known that during development, children display less coordinated movements than adults and have incomplete development of their sensorimotor system (Moon et al., 2015). Children also face an even higher amount of ever changing environmental demands due to the growth of their body; especially their lower extremities. Despite reaching similar levels of adaptation to visuomotor transformations or force field application, children display less accurate movements and increased variability in goal-directed arm movements (Contreras-Vidal, 2006; Contreras-Vidal et al., 2005; Jansen-Osmann et al., 2002; Takahashi et al., 2003). Refinements in the accuracy, speed and smoothness of goal-directed arm movements typically occur with increasing age (Contreras-Vidal, 2006). Potentially, the incomplete development of a child's sensorimotor system and deficits in integrating the current state of the system contribute to the increased amount of errors in completing goal-directed upper extremity movements. Additionally, it is possible that children also have less robust internal models underlying their movements, thus, they are unable to address the ever changing dynamics of their limbs (Shadmehr & Mussa-Ivaldi, 1994).

While the development and execution of upper extremity motor plans have been well explored, little research has been conducted exploring how individuals, specifically children, plan and execute rapid, goal-directed motor tasks with the lower extremities. Since the lower extremities are vital for daily locomotion, it is possible that the formulation of internal models for lower extremity motor tasks is planned differently than an upper extremity movement. Moreover, the amount of time that it takes to process and integrate an appropriate amount of visual and proprioceptive information before an individual can accurately execute a goal-directed movement is not well understood. Thus, the purpose of the current study is to interrogate how the amount of motor planning time provided to a child may influence the preparation and execution of a goal-directed knee extension motor task.

2. Methods

Twelve typically developing children (7 females; mean age: 8.2 ± 1.8 years) and 13 healthy adults (7 females; mean age: 26.0 ± 6 years; see Table 1) participated in this research study. All experimental procedures were approved by the University of Nebraska Medical Center Institutional Review Board. All adult subjects signed a written informed consent form and a parent of each child participant gave consent for their child to participate. Additionally, all children provided assent to participate.

Subjects were seated in an adjustable height chair and a table was placed in front of them in such a way that all vision of their lower extremities was occluded (Figure 1). The back of the chair was also adjustable so that the subject could be appropriately positioned so that their knees were at the edge of the chair and were bent at 90 degrees. During the data collection, neither of the subject's feet was in contact with the floor. We selected to occlude the vision of the lower extremities in order to limit the amount of visual feedback utilized

during the experiment by the subjects so that they must rely on their current internal model to make feed-forward predictions. The subjects used their dominant leg for all experimental procedures. Leg dominance was determined by self-report from the adult subjects and from self-report plus kicking a soccer ball for the children subjects. The dominant leg was strapped down across the thigh during all procedures in order to eliminate excessive leg movements. A gyroscope was attached with an elastic strap to the subject's leg directly above the lateral malleolus. The gyroscope captured the position of each subject's lower leg and displayed it on a computer screen ~1 meter in front of the subjects. The leg position was sampled at 125 Hz using a custom computer program and provided each subject with real-time feedback of where their lower leg was in space. At the beginning of the data collection, all subjects performed one maximal range of motion (ROM) task in which they were instructed to extend their knee as far as possible and hold it there for three seconds. This maximum ROM was used to calculate 25 and 75% maximum ROM targets that were used in the experiment for each individual.

All subjects completed one session consisting of a goal directed, target-matching task. In this target-matching task, subjects were instructed to extend their leg as fast and accurately as possible so that a cursor on the computer screen that represented their leg position was fully inside a target displayed on the computer screen. Targets were randomly placed at either 25% or 75% of the subject's max ROM. Each trial began when the subject had placed their leg in the initial starting position where their knee was flexed at 90 degrees. At this point in time, the target was displayed, after which a go-cue was signaled. The go-cues were presented at variable time lags of 0 ms, 1000 ms, or 2000 ms long. The go-cue was a simultaneous visual and auditory cue. The auditory cue was a beep and the visual cue was that the cursor representing the subject's leg position turned from red to green. When the subject successfully matched the target with his/her leg, the target and the cursor representing the subject's leg "exploded" on the screen and a auditory reward (i.e., train whistle sound) also indicated that the subject had successfully matched the target. Each subject completed two blocks of 60 trials with a rest of at least 2 minutes in between each block. All subjects completed 20 trials at each target location and each time lag for a total of 120 trials. Subjects were instructed to remain as still as possible in between each trial in order to prevent early movement; additionally, if the subject's leg was not placed at the original starting position (e.g., 90 degrees), the trial would not begin.

All data was processed with a custom Matlab program (Math Works Inc., Natick, MA, USA). The leg position data was filtered using a fourth order Butterworth filter with a cut-off at 6 Hz. The variables of interest were the reaction times, movement times, and accuracy of movement (i.e., amount of overshoot/undershoot). Reaction time was the time calculated from the moment the go-cue was given to the moment when the gyroscope indicated leg movement (Figure 2). Movement time was calculated from the moment the leg movement began to the time when the target was reached. Reaction times and movement times are reported as seconds. The amount of overshoot and undershoot was calculated based on the first maximal position reached by the leg. If this first maximal position was below the target, this was defined as undershoot; if the first maximal position was above the target, then it was defined as overshoot. The amount of overshoot and undershoot are reported as degrees.

Any trials where the gyroscope was not stationary (i.e., the subject's leg was already in motion) at the beginning of the trial was discarded from analyses.

All statistical analyses were performed using IBM SPSS Statistics 22 statistical software (IBM Corp., Armonk, NY, USA). The data was log transformed for all statistical analyses. Separate mixed three-way repeated measures ANOVAs (2 Groups $\times$ 2 Locations $\times$ 3 Motor Planning Times) were used to compare the differences of the variables of interest between groups, locations, and planning times. All ANOVA calculations were followed with a Fisher's least significant difference post hoc statistics. The alpha level of 0.05 was used to interrogate all data for significance. The data is reported as the mean $\pm$ standard error of the mean (SEM) of the non-log transformed data. Only the significant main effects and interactions are reported.

3. Results

3.1 Reaction Time

For reaction time, there were significant main effects for motor planning time ($p < 0.001$) and group ($p = 0.019$). Our post hoc analyses indicated that there was a significantly longer reaction time at the zero motor planning time interval than there was at the one second and two seconds motor planning time intervals ($p < 0.001$; Figure 3A). There was no difference between the reaction times of the one second and the two second motor planning time interval trials ($p > 0.05$). Based on the group main effect, the children displayed slower reaction times for all targets and motor planning times (Figure 3B). Additionally, there was a significant motor planning time $\times$ group interaction ($p = 0.025$; Figure 3C). Post hoc analyses displayed that the children had significantly slower reactions times at all motor planning time intervals than the adult subjects ($p \leq 0.005$). Finally, there was no main effect for location ($p > 0.05$).

3.2 Movement Time

For the movement time analyses, there were significant main effects for location ($p < 0.001$) and group ($p = 0.013$). The post hoc analysis indicated that it took longer to reach the target at 75% max ROM than the time it took to reach the target placed at 25% max ROM (25% Target: 3.19 ± 0.04 sec.; 75% Target: 3.864 ± 0.07 sec.). However, this result was expected since the target at 75% max ROM was farther away from the starting position than the target placed at 25% max ROM. The group main effect indicated that the children took longer to accurately reach the target regardless of target location or motor planning time (Figure 4A). Additionally, there was a significant location $\times$ group interaction ($p = 0.026$; Figure 4B). Post hoc analyses for this interaction displayed that children took longer to reach both targets than the adult subjects, regardless of the motor planning time provided to them ($p \leq 0.002$). There was no main effect for motor planning time ($p > 0.05$).

3.3 Accuracy

There were significant main effects for location and group for both undershooting and overshooting the target ($p \leq 0.002$). Post hoc analysis indicated that there was a significantly larger amount of undershoot for the target at 75% max ROM (Figure 5A), and a

significantly larger amount of overshoot for the target at 25% max ROM (Figure 5C) regardless of motor planning time or group. Furthermore, post hoc analyses for the group main effects indicated that the children had a significantly larger amount of undershoot and overshoot overall regardless of target location or motor planning time (Figure 5B/5D). Additionally, there was a significant time main effect for overshooting the target ($p=0.049$; Figure 5E). Post hoc analyses for this main effect indicated that there was a higher amount of overshoot following the zero motor planning time interval than the one second motor planning time interval ($p=0.013$), and there was a trend towards significance between the zero motor planning time interval and the two second motor planning time interval regardless of target location ($p=0.09$). Additionally, there was no difference between the amount of overshoot of the one second and two second motor planning intervals ($p>0.05$).

4. Discussion

The results of this study showed that the amount of motor planning time provided to an individual may influence the reaction time and accuracy of a leg movement. When given no additional motor planning time after target presentation, both the adults and children had slower reaction times regardless of the target location. Additionally, the children displayed slower reaction times than the adults for all motor planning times given to them regardless of target location. The children also had longer movement times than the adults to both target locations regardless of the amount of motor planning times provided. All subjects displayed a greater amount of overshoot for targets placed at 25% max ROM and a greater amount of undershoot for targets placed at 75% max ROM. The amount of overshoot was greater for all subjects when no motor planning time was provided after target presentation. Furthermore, the children were less accurate and had an overall greater amount of error in their leg movements than the adults for all targets and motor planning times. Overall these results suggest that children may formulate motor plans for the lower extremities movements at a slower rate than adults and the selected motor plans are less accurate. Potentially, the aberrant motor plans may indicate that the children have not established a robust internal model that can be used to accurately control the lower extremity movements.

Our results of slower reaction times following shorter motor planning time intervals supports that the participants were using a feed-forward planning strategy. This notion is supported by our results that showed that when subjects were provided with no motor planning time, they had slower reaction times, which suggests that they were still altering the internal model to meet task demands before movement execution began. Additionally, the amount of overshoot was greater when no motor planning time was provided suggesting that the motor plan might not have been adequately formulated before the beginning of the leg movement. The slowed reaction time was more pronounced for the children, which is in agreement with prior investigations that have shown that children require longer planning times for upper limb goal-directed movements (Bo, Contreras-Vidal, Kagerer, & Clark, 2006; Favilla, 2006; Yan, Thomas, Stelmach, & Thomas, 2000). Potentially the motor planning differences seen in our study and others may reflect that adults may have a better internal model of the changes in the velocity and amplitude of their leg goal-directed movements due to the fact that they have had more motor experiences. The development of internal models is dependent upon both previous experience and proper integration of the

visual and proprioceptive signals. Previous investigations have shown that with practice children are able to improve goal-directed reaching or drawing tasks; however, younger children who lack more experience in such tasks have been seen to be limited in these improvements (Contreras-Vidal et al., 2005; Thomas, Yan, & Stelmach, 2000). In a similar light, it is possible that the deficits in motor planning of our child subjects may be related to limited motor experiences involving the lower extremities; including which utilizing more mature or adult like gait patterns. In addition, the growth of their lower extremities may have resulted in their movement limb dynamics being more novel (Jansen-Osmann et al., 2002). These novel limb dynamics may have resulted in the internal model being more primitive or incomplete. We suspect that this may have resulted in the children taking longer time to adequately process and integrate the sensory information for accurately predicting a successful motor outcome.

The tendency to overshoot the target placed at 25% max ROM and undershoot the 75% max ROM in all subjects was not completely expected. However, the amount of error that occurred in either direction was relatively similar or slightly less than the amount of error seen in upper extremity goal-directed motor tasks (Contreras-Vidal, 2006; Jansen-Osmann et al., 2002). It has been thought that accuracy errors in a goal directed movement task are more commonly undershooting errors because an overshooting error is more costly to the motor system (Elliott et al., 2010). An overshoot error may be more costly because the limb must travel further than the target and must overcome a major directional change at the point of reversal to go back to the target. Previous research has shown that children have greater difficulty consistently controlling and executing the amplitude of goal-directed motor tasks (Fox, Moon, Kwon, Chen, & Christou, 2014; Takahashi et al., 2003). Hence, it is possible that planning the amplitude of the goal directed lower limb motor tasks may have also resulted in the initial target matching errors. We suspect that these errors may have arisen from inaccuracies in the timings of the muscle activations and/or co-contractions that occurred as the limb approached the target.

Our results also showed that the children had slower movement times to successfully arrive at the target in either location. Previous investigations exploring the developmental features of rapid arm movements have found that young children typically display slower movements than young adults as well as a higher amount of corrective adjustments towards the end of the movement (Yan et al., 2000). Hence, the slower movement times seen here likely reflect that the children tended to have greater initial errors in their feed forward predictions of the motor synergies necessary to place the lower leg in the target location, and that they needed additional time to correct for these errors in order to arrive at the target location.

We suspect that the differences in the motor planning of the adults and children seen in this investigation may be partly related to the structural and functional maturation of the sensorimotor cortices. Our conjecture is supported by a prior longitudinal investigation that revealed that there is a distinct loss of the grey matter volume within the sensorimotor cortices and parietal cortices after puberty (Gogtay et al., 2004). The grey matter changes are presumed to be related to the synaptic pruning that is associated with the optimization of the neuronal groups that comprise the sensorimotor cortices. Recent investigations have also

shown that children have less prominent changes in the sensorimotor cortical oscillations at the beta frequency (15–30 Hz) during the motor planning period and may recruit compensatory cortical areas when formulating a motor plan (Cheyne, Jobst, Tesan, Crain, & Johnson, 2014; Pangelinan, Kagerer, Momen, Hatfield, & Clark, 2011; Wilson et al., 2010). Further interrogation of the relationship between the cortical dynamics while performing a leg target matching task may provide unique insight on why children tend to take longer to plan, have greater errors and take longer to match a given target.

5. Conclusions

In conclusion, our results indicate that the internal models for goal-directed knee extension movements are planned and executed similarly to upper extremity movements. When subjects received no pertinent information useful for motor planning before the signal to move, their reaction times slowed and motor accuracy was compromised. Based on our results, we suspect that children may not have the proper experience to accurately predict the sensory and motor demands of a motor task, thus leading to decreased accuracy no matter how much motor planning time is provided.

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Highlights

- Pre-movement motor planning time may influence the reaction time and accuracy of a movement.
- Children had slower reaction and movement times to all targets than adults at all planning times.
- Children were less accurate than adults at all targets for all motor planning times.
- Children may not have a robust internal model that can be used to predict goal-directed movements.

Figure 1.

The experimental set up with the subject seated in the adjustable height chair and the table occluding the vision of their lower extremities. The computer screen is placed ~1 meter in front of the subject and the gyroscope is attached to the subject's leg directly above the lateral malleolus. The square on the screen provides the subject with feedback about the leg's position.

Figure 2.

An exemplary graph of the movement of the gyroscope during the target matching task. The dotted lines represent the boundaries and centroid of the target box. The dark grey line represents the leg's movement as measured by the gyroscope. The shaded grey region highlights the subject's reaction time after the go signal was presented. The black circle at the top of the curve represents the first maximum in the movement, which is used to calculate the amount of accuracy. In this exemplary graph, the first maximum is above the target; therefore, it is an overshoot error.

Figure 3.

A) The motor planning time main effect for reaction time, **B)** The group main effect for reaction time, **C)** The motor planning time $\times$ group interaction for reaction time. The light grey bars represent the adults and the dark grey bars represent the children. * indicates $p < 0.05$.

Figure 4.

A) The group main effect for movement time. **B)** The target location $\times$ group interaction for movement time. The dark grey bars represent the children and the light grey bars represent the adults. * indicates $p < 0.05$.

Figure 5.

A) The target location main effect for the amount of undershoot, **B)** The group main effect for the amount of undershoot, **C)** The target location main effect for the amount of overshoot, **D)** The group main effect for the amount of overshoot, **E)** The motor planning time main effect for the amount of overshoot. * indicates $p < 0.05$.

Table 1

Subject Characteristics

Adult Subjects					Child Subjects				
Subject	Gender	Age (years)	Height (cm)	Weight (kg)	Subject	Gender	Age (years)	Height (cm)	Weight (kg)
1	M	26	172.7	65.8	1	F	9	136.0	29.0
2	F	27	168.9	61.2	2	M	6	130.0	23.0
3	F	31	163.0	59.9	3	F	9	137.0	29.2
4	M	42	174.5	73.4	4	F	12	152.0	41.2
5	M	21	176.5	68.0	5	M	8	133.5	30.5
6	F	21	164.0	61.0	6	M	10	150.5	43.2
7	M	23	178.0	74.0	7	F	9	144.5	37.5
8	F	23	173.5	60.7	8	F	7	133.0	27.8
9	F	22	165.6	74.8	9	F	9	133.0	30.2
10	M	23	182.5	77.5	10	M	6	127.0	28.8
11	M	23	189.0	95.0	11	M	6	120.0	20.7
12	F	32	161.5	53.7	12	F	7	129.0	23.4
13	F	24	174.0	75.8					
Average	7 female	26 ± 6	172.6 ± 8	69.3 ± 11	Average	7 female	8.2 ± 1.8	135.5 ± 9.4	30.4 ± 7