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Development of infant leg coordination: Exploiting passive torques[☆]

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ABSTRACT

Leg joint coordination systematically changes over the first months of life, yet there is minimal data on the underlying change in muscle torques that might account for this change in coordination. The purpose of this study is to investigate the contribution of torque changes to early changes in leg joint coordination. Kicking actions were analyzed of 10 full-term infants between 6 and 15-weeks of age using three-dimensional kinematics and kinetics. We found 11 of 15 joint angle pairs demonstrated a change from more in-phase intralimb coordination at 6-weeks to less in-phase coordination at 15-weeks. Although the magnitude of joint torques normalized to the mass of the leg remained relatively consistent, we noted more complex patterns of torque component contribution across ages. By focusing on the change in torques associated with hip–knee joint coordination, we found that less in-phase hip–knee joint coordination at 15-weeks was associated with decreased influence of knee muscle torque and increased influence of knee gravitational and motion-dependent torques, supporting that infants coordinate hip muscle torque with passive knee gravitational and motion-dependent torques to generate kicks with reduced active knee muscle torque. We propose that between 6 and 15-weeks of age less in-phase hip–knee coordination emerges as infants exploit passive dynamics in the coordination of hip and knee motions.

[☆] John Scholz, a dear friend and colleague, is deceased at the time of publication. John contributed his mighty intellect and generosity to the creation and completion of this research.

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1. Introduction

Early motor skill acquisition is a dynamic process of exploration and discovery in which the spontaneous movements of infancy are adaptively modulated into task-specific actions, such as reaching, crawling, and walking (Gibson & Pick, 2000; Thelen & Smith, 1994). Infants use multiple end effectors for goal directed action during this discovery process. Obvious end effectors include the arms and hands, but legs and feet and even mouths are harnessed for task-specific action. For example, infants as young as 3–4 months of age produce task-specific action by activating a musical mobile with their legs (Angulo-Kinzler, Ulrich, & Thelen, 2002; Chen, Fetters, Holt, & Saltzman, 2002; Heathcock, Bhat, Lobo, & Galloway, 2004; Sargent, Schweighofer, Kubo, & Fetters, 2014) or by using sucking behaviors to focus and refocus the image on a slide (Siqueland & DeLucia, 1969). The transition from spontaneous to task-specific action has been studied and well described for the upper extremities during the development of reaching at many levels of analysis, including kinematic and kinetic (Bhat, Heathcock, & Galloway, 2005; Konczak, Borutta, Topka, & Dichgans, 1995; Thelen et al., 1993). However, although the lower extremities develop reaching abilities prior to the upper extremities when given the environmental opportunity (Galloway & Thelen, 2004) we know much less about the development of control of these end effectors, particularly with regard to the control of muscle forces as task-specific action emerges (Jensen, Schneider, Ulrich, & Zernicke, 1994; Jensen, Thelen, Ulrich, Schneider, & Zernicke, 1995; Schneider, Zernicke, Ulrich, Jensen, & Thelen, 1990).

Here, we longitudinally investigate the dynamics of spontaneous leg movements in typically developing infants during a developmental window in which the joints of the lower extremities transition from an ***in-phase*** pattern of simultaneous flexion and extension at all joints to ***less in-phase*** patterns in which combinations of flexion at one joint occurs with extension at another joint (Fetters, Chen, Jonsdottir, & Tronick, 2004; Jeng, Chen, & Yau, 2002; Jensen et al., 1995; Piek, 1996; Thelen, 1985; Vaal, van Soest, Hopkins, Sie, & van der Knapp, 2000). This change in coordination occurs prior to an apparent task, but may result from the adaptive modulation of the infant's spontaneous movements in response to gravitational constraints. We propose that the infant's "task" during this change in coordination may be to ***explore the dynamics of their leg actions*** while moving in a gravitational field (Jensen et al., 1994; Jensen et al., 1995; Schneider et al., 1990). Therefore, investigating the contribution of dynamics to early changes in leg joint coordination is a logical starting point for understanding the process by which spontaneous leg movements adaptively modulate in response to environmental constraints, such as gravity. It also serves as a necessary foundation for understanding the emergence of early task-specific leg actions which require selective control of the joints, such as foot reaching (Galloway & Thelen, 2004).

Understanding the processes which support the early transition to less in-phase leg joint coordination requires an understanding of the dynamic control that emerges during this transition. Control of leg movements requires not only the generation of active muscle forces, but the anticipation and control for the effects of gravity and for the emergent passive forces that are generated as a result of active muscle force generation (Bernstein, 1967; Jensen et al., 1994; Jensen et al., 1995; Schneider et al., 1990). Therefore, one of the earliest ways infants adaptively modulate their spontaneous movements may be by anticipating and controlling for the effects of passive forces which occur as they move within a gravitational environment. Preliminary but limited data suggest that during spontaneous kicking, 3-month old infants adjust their muscle (MUS) torques in relation to differing passive gravitational (GRA) and motion-dependent (MDT) torques as a result of changes in the intensity of the kicking motion (Schneider et al., 1990) and changes in the orientation of the limb relative to gravity (Jensen et al., 1994). These results support that infants as young as 3-months of age modulate their MUS torques in response to differing environmental conditions. However the results are predicated on a limited number of kicks from infants at only one age and with the use of a two-dimensional (2D) model of the dynamics. A 2D model does not account for the torques that occur from the rotational aspects of movement, such as hip abduction/adduction, hip external/internal rotation, and ankle eversion/inversion. Infants demonstrate considerable hip abduction and external rotation during their kicking motion supporting that a 2D model is insufficient to accurately estimate joint torques and a three-dimensional (3D) model is necessary. Additionally, previous studies did not investigate the contribution of torque changes to the early transition to less in-phase leg joint coordination.

Previous research in control of adult reaching and circle drawing supports that the greater skill exhibited by the dominant arm, compared to the non-dominant arm, may be related to its ability to anticipate and compensate for the effect of interaction forces (Sainburg & Kalakanis, 2000; Tseng, Scholz, & Galloway, 2009). In these studies, the shoulder is identified as the driver of the action, whereas the elbow must "manage" the resultant forces generated by the shoulder yet still accomplish the reaching or circle drawing task. Similar to this work, we are interested in the knee as "managing" the resultant forces generated by the hip during spontaneous kicking between 6 and 15-weeks of age and how this contributes to the transition from in-phase to less in-phase coordination during infant spontaneous kicking.

Here, we investigated the relation of the torque changes to the transition in coordination using a large data set and a 3D model to compute both the kinematics and kinetics of the leg actions. We analyzed spontaneous leg movements between 6 and 15-weeks of age; a developmental period during which intralimb leg joint coordination changes from a predominately in-phase coordination of synchronous flexion and extension of the hip, knee, and ankle joints to less in-phase hip, knee, and ankle coordination (Fetters et al., 2004; Jeng et al., 2002; Jensen et al., 1995; Piek, 1996; Thelen, 1985; Vaal et al., 2000). We analyzed supine leg movements because this position is ecologically valid for infants and exerts fewer external constraints on spontaneous kicking than other positions: prone and sitting leg movements are constrained by the support surface, vertical and angled leg movements are constrained by the strong influence of gravity (Jensen et al., 1994), and leg movements when suspended over a moving treadmill are entrained by the action of the treadmill (Thelen, 1986).