

Characterized Developmental Inter-Joint Coordination During Deep Squat: Implications for Pediatric Knee Overuse

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INTRODUCTION: The debate surrounding early sports specialization in children centers on the significant potential for overuse injuries, often compounded by structural immaturity of the musculoskeletal structures and developmental limitations of their central nervous system control. The deep squat movement serves as an essential functional movement in both activities of daily living and sports performance, fundamentally requiring optimal multiple coordinated internal joints to control postural stability. In this study, we aimed to examine the relationship between the development of the knee-hip joint coordination pattern during deep squat movement and both chronological age and physical growth stage in pediatric populations. Through this examination, we aimed to delineate the developmental characteristics of inter-joint coordination in the knee and hip joints to prevent overuse syndrome.

METHODS: This cross-sectional study included 208 elementary and junior high school students (102 male and 106 female). Participants were initially stratified into three groups based on their chronological age: lower elementary (ages 6–9; n=79), upper elementary (ages 10–12; n=80), and pre-teen (ages 13–14; n=49). Biological maturity was determined using the Maturity Offset method (Mirwald et al., 2002) to estimate peak height velocity (PHVA). Based on age, the participants were categorized into pre-spurt (n=104), during-spurt (n=50), and post-spurt (n=54) physical growth stages. Participants who reported active lower-limb or lumbar pain at the time of the survey were excluded. Each participant performed a deep squat, descending to the lowest possible position with the buttocks as close to the heels as possible, arms flexed at 90°, and both feet flat on the floor. The movement was captured using a video camera positioned on the left side of the sagittal plane (30 fps). The two-dimensional coordinates of the key body landmarks (shoulders, hips, knees, and ankles) were collected from each video frame using a skeleton tracking library (MediaPipe Pose). The resulting hip and knee joint angles were calculated using specialized programming software (MATLAB). Inter-joint coordination was quantified as the total deviation area between the ideal linear line (representing perfect hip-knee flexion refashion concurrence) and the actual movement line (Fig. 1). This total deviation was further divided into under- and upper-deviation areas, indicating the degree of developmental reliance on knee and hip flexion, respectively. Furthermore, the ankle joint range of motion (ROM) was assessed using the dorsiflexion angle. The same physical therapist categorized the overall deep squat performance into three achievement levels: "complete", "inadequate," and "incomplete." The relationship between the three deviation areas was the outcome variable, and independent factors, including age group, sex, physical growth stage, ankle dorsiflexion ROM, and deep squat performance level, were statistically examined using Generalized Linear Mixed Models (GLMM) or the Kruskal-Wallis test. Ethical approval was obtained from the Human Ethics Committee of the Ibaraki Prefectural University of Health Sciences (Approval # e239), and written informed consent was obtained from the parents or legal guardians of the participants.

RESULTS SECTION: The GLMM yielded a robust predictive model for the total deviation area, characterized by a pseudo-determination coefficient of $R^2 = .569$ and an intraclass correlation coefficient of $ICC = .484$. A significant decrease in the total deviation area was observed, corresponding to the advancement of physical growth stages ($p = .003$) (Fig. 2). Conversely, the total deviation area showed a significant increase in the group categorized as performing "incomplete" deep squat performance ($p = .037$). The total deviation area was not significantly related to chronological age ($p = .490$), sex ($p = .242$), or ankle dorsiflexion ROM ($p = .396$). The results of the Kruskal-Wallis test indicated that the under-deviation area (knee flexion reliance) exhibited a significant decrease with the development of physical growth stages ($p < .001$); however, the upper-deviation area showed no significant differences across physical growth stages ($p = .513$).

DISCUSSION: The findings suggest that the development of inter-joint coordination between the hip and knee during functional deep squatting is intrinsically linked to an individual's physical growth stage (biological maturity) rather than solely to chronological age. This developmental shift is characterized by a progressive decrease in the reliance on knee flexion. Furthermore, the association between minimal joint deviation and superior movement achievement underscores the clinical importance of efficient coordination.

SIGNIFICANCE/CLINICAL RELEVANCE: Preventing knee overuse in children requires interventions targeting hip-knee coordination and hip utilization according to the child's specific physical growth stage.

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IMAGES AND TABLES:

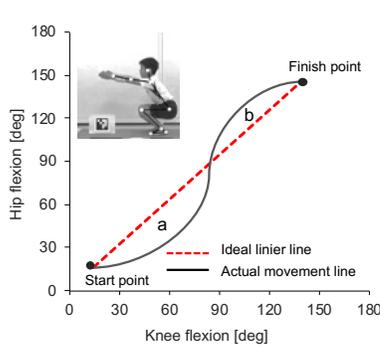


Fig. 1 Inter-Joint Coordination

a + b: the total deviation area
a: the under-deviation area
b: the upper-deviation area

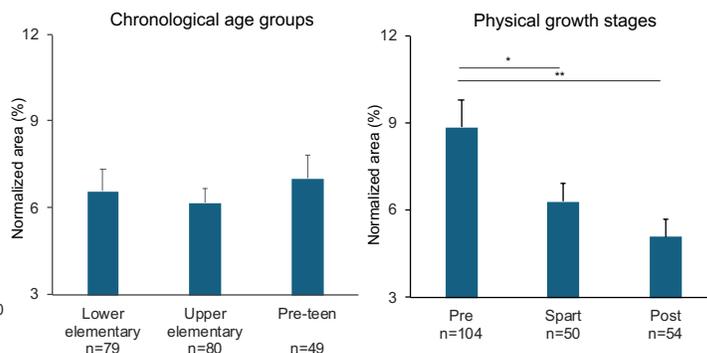


Fig. 2 Estimated the total deviation areas by GLMM

Error bar: SE
* $p < .05$
** $p < .001$