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THE MECHANICS OF THE SIT-TO-STAND
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David Michael Wisner

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Eugene W. Brown
Major professor

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# THE MECHANICS OF THE SIT-TO-STAND MOVEMENT IN YOUNG CHILDREN

By

David Michael Wisner

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# ABSTRACT

## THE MECHANICS OF THE SIT-TO-STAND MOVEMENT IN YOUNG CHILDREN

By

David Michael Wisner

Functioning in daily life as an independent human being involves having the ability to stand up from a seated position, yet little information is available on the sit-to-stand (STS) movement in children. The primary purpose of the present study was to assess the mechanics of the STS movement in young children. A secondary purpose was to compare the biomechanics of the STS movement among children of different ages. The subjects were 12 children who fell into one of three age groups: 12-18 months (N = 5), 24-36 months (N = 3), and 48-60 months (N = 4). The subjects were videotaped as they stood up from a seat adjusted to each subject's knee height. Data on forces at the buttocks and at the feet were collected simultaneously from a force platform mounted on the stool and a force platform located beneath the feet. The kinematic and kinetic variables obtained or derived from the analysis of the video and force records included movement times; joint ranges of motion; peak hip flexion, hip extension, and knee extension velocities; velocity of the whole-body center of gravity; forces at the buttocks and feet; and peak hip and knee joint moments. The results of the study indicated that the overall pattern of the STS movement is well-developed even in the youngest children and is similar to that seen in adults. These similarities include: (a) the overall joint motion pattern, in which hip flexion and ankle dorsiflexion characterize the early part of the movement while extension of the hip, knee, and ankle (i.e., plantar flexion) occur in the

latter part of the movement; and (b) the pattern of forces at the buttocks and the feet, which included three types of forces: a posteriorly-directed, propulsive horizontal force at the buttocks that initiates the movement; a vertical, propulsive force at the feet; and an anteriorly-directed, braking horizontal force at the feet which acts to check the forward momentum of the body. Overall, the STS movement in the children was characterized by fast movement times (c. 1.2 s), relatively fast joint angular velocities, hip joint moments that were greater in magnitude than knee joint moments, and the center of gravity being located behind the base of support at seat-off. There was a trend toward increasing joint ranges of motion, velocities, forces, and moments with increasing age, with the oldest children having results quite similar to adults. These results suggest that the oldest children employed a strategy of transferring momentum from the upper body to the lower body during the movement as seen in younger adults. While the younger children exhibited many of the characteristics of this strategy, they also used elements of a strategy in which the goal of upper body movements is to bring the center of gravity close to the base of support at the time of seat-off, probably due to a relative lack of balance and postural control as compared to the older children and adults. While this study provides much-needed normative data on able-bodied children, additional research needs to be done on how the mechanics of the STS movement in children are affected by elements of seat design, and on the mechanics of the STS movement in children with disabilities.

For my wife, whose love, patience, and gentle prodding helped see me to the end of this project; and for my father, whose desire it always was to see me earn my doctorate.

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# INTRODUCTION

Functioning in daily life as an independent human being involves having the ability to stand up from a seated position, walk, run, and change positions when seated, standing, or lying down. In other words, mobility is essential if one is to be truly independent (Dawson, Hendershot, & Fulton, 1987; Shumway-Cook & Woollacott, 1995, p. 239). In fact, for those individuals who have a disability (whether congenital or acquired through some traumatic injury) one of the major goals of the rehabilitation process is to help the individual regain as much mobility as possible (Shumway-Cook & Woollacott, 1995, p. 239). Often times mobility is thought of principally in terms of locomotion, but the ability to change position from sitting to standing is an equally fundamental part of mobility (Shumway-Cook & Woollacott, 1995, p.257).

The ability to rise from a seated position on the floor to a standing position without relying on external support is a benchmark of normal motor development that typically occurs around eight months of age and is an important prerequisite for the development of independent walking (Bayley, 1969; McGraw, 1943). While children continue to sit on the floor for many years after they develop the ability to stand, around twelve months of age many children are introduced to seats and chairs of appropriate size for their stature. From this point on, rising from a seated position on a chair will become increasingly more common until it eventually becomes the primary type of sit-to-stand (STS) transfer. Many factors likely influence a child's ability to rise from a seated position, including the child's physical abilities, motor development, and the design of the chair.

While the ability to rise from a supine position to a standing position develops quite naturally in most children, those who have a disability often have great difficulty with this skill, and will therefore more than likely have difficulty rising to a standing position from a chair (Shumway-Cook & Woollacott, 1995, p. 260; VanSant, 1988). However, despite the fact that a great deal of attention has been paid by researchers and clinicians on the development of initial standing from a supine position, which occurs around eight months of age, and on the performance in adults (both those with and without disabilities) of rising from a seated position on a chair (ranging in age from 18 to 90 years of age), very little research has been conducted on the ability of able-bodied children to rise to a standing position from a seated position on a chair, let alone the ability of children with disabilities to perform the sit-to-stand transfer. In fact, to date only five studies out of the approximately sixty-five studies on the sit-to-stand movement have involved children (Brugnolotti, 1992; Cahill, Carr, & Adams, 1999; Francis, 1987; McMillan, 1998; and Scholz & Brandt, 1997). Of these only the study by Cahill, et al. investigated the mechanics of the movement; the others focused on developmental and motor control aspects of the movement. Because rehabilitation specialists rely on normative data from able-bodied individuals to distinguish normal motor behavior from abnormal motor behavior when assessing patients with a disability and developing a treatment plan (Shumway-Cook & Woollacott, 1995, chap. 5), the relative lack of normative data on the mechanics of the sit-to-stand transfer in children has resulted in a serious limitation in helping children with disabilities (re)gain mobility and independence (L.J. MacDonald, personal communication, May 20, 2001; D. Silkwood-Sherer, personal communication, September 4, 2001). It is this general lack of information on the ability of children to rise from a seated position that this study seeks to address.

## *Purpose of the Study*

The primary purpose of the present study was to assess the kinematics and kinetics of the movement pattern that occurs when a child rises from a seated position on a seat to a standing position. This type of biomechanical analysis provides the information rehabilitation specialists need to better aid children with disabilities in their ability to stand.

A secondary purpose was to compare the biomechanics of rising from a seated position among children of different ages in order to determine if any age-related differences exist which can be used to predict developmental patterns. Such a comparison helps to fill in the knowledge gap that presently exists and is of use for practitioners who work with children on a day-to-day basis.

## *A Definition of the Sit-to-Stand Movement*

The sit-to-stand (STS) movement involves the smooth motion of an individual from a stationary seated position to a standing position. The STS movement has been frequently divided into a number of phases (see "Phases of the STS Movement" in Chapter 2) for descriptive purposes. In the present study, the STS movement is divided into four phases (see "Phases of the STS Movement" in Chapter 2 for a rationale behind the selection of these phases; each of these phases and the events that delineate each are illustrated in Figure 1):

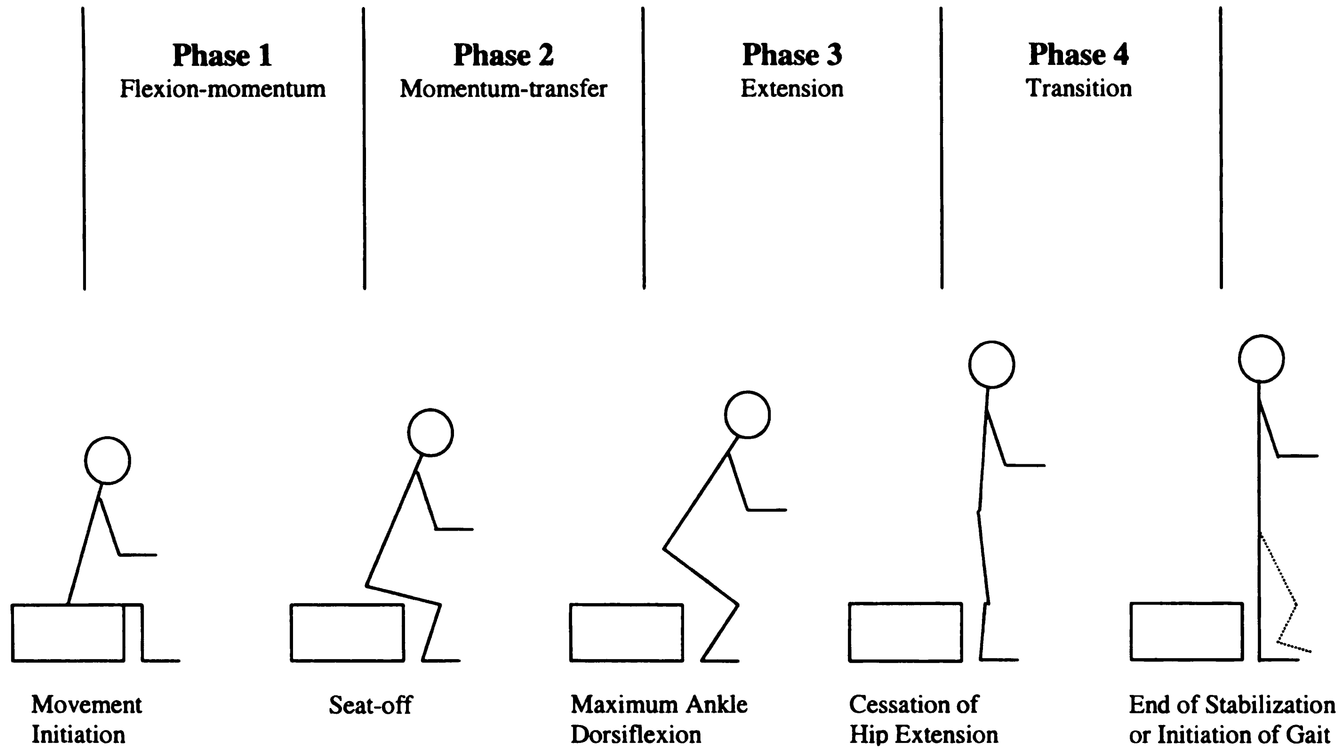


**Figure 1.** Phases and delineating events of the sit-to-stand movement.

(1) Flexion-momentum Phase: from movement initiation until just before the buttocks lift off the seat.

(2) Momentum-transfer Phase: from lift-off until maximum dorsiflexion of the ankles is reached.

(3) Extension Phase: from just after maximum dorsiflexion of the ankles is reached until the hips first cease to extend.

(4) Transition Phase: from just after the hips cease to extend until all motion associated with stabilization from rising is completed, if the individual intends to remain standing, or until a subsequent movement pattern, such as walking, is initiated.

*Definition of Joint Angles*

The present study used a two-dimensional sagittal plane representation of the body. Angular positions of the various joints of the body in anatomical position is defined to be 0°. In the case of the hip and knee joints, flexion results in an increase in the joint angle. In the case of the ankle joint, dorsiflexion results in increasing degrees "of dorsiflexion", while plantar flexion results in increasing degrees "of plantar flexion" (see Figure 2).

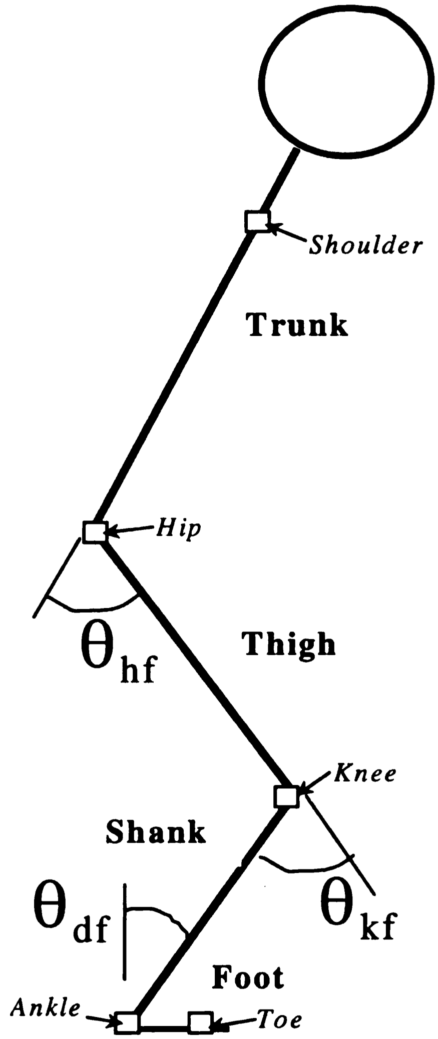


**Figure 2.** Four-segment, two-dimensional biomechanical model. The four segments consist of the trunk, thigh, shank, and foot. The joints (and specific bony landmarks) that define each segment are the shoulder (acromion process), hip (greater trochanter), knee (center of knee joint), ankle (lateral malleolus), and toe (base of the fifth metatarsal). The joint angles are defined as follows: $\theta_{df}$ = degrees of ankle dorsiflexion, $\theta_{kf}$ = degrees of knee flexion, and $\theta_{hf}$ = degrees of hip flexion.

## REVIEW OF LITERATURE

The following review of literature is divided into two major sections. The sit-to-stand movement is discussed more generally in the first section, including the phases of the movement, its fundamental mechanics, and the factors (e.g., initial position, chair design, function ability) that affect the performance of the movement. The second section is devoted more specifically to the sit-to-stand movement in children, including developmental topics related to the movement.

### *The Sit-to-Stand Movement*

What follows is a description of the STS movement, beginning with the various ways that the movement has been divided into its fundamental phases. This is followed by an attempt to synthesize these various methods of dividing the movement and presenting a rationale for the method used in the present study. The fundamental mechanics of the STS movements and the factors that affect the fundamental mechanics of the movement are then described.

#### *Phases of the Sit-to-Stand Movement*

As noted in the Introduction, the STS movement involves rising from a seated position to a standing position from which locomotion or some other motor task can be initiated. Although the STS is a common movement for most people, it has only recently been studied in some depth (the first study was conducted in 1963 by Jones, Hanson, Miller, and Bossom). There are as yet no defined or universally accepted phases of the

movement. To date, there have been several different ways of dividing the movement into its component phases, although as shall be seen, many of these defined phases are very similar to one another. What follows is a description of the various phases into which authors have divided the STS movement, and the definitions of these phases.

The first to define phases of the STS were Kelley, Dainis, and Wood (1976) who simply divided the movement into two phases, a Forward-flexion Phase, from initiation of movement until maximum flexion of the trunk, and an Extension Phase, from maximum flexion of the trunk to upright stance.

More recently, Schenkman and colleagues (Ikeda, Schenkman, Riley, & Hodge, 1991; Jeng, Schenkman, Riley, & Lin, 1990; Schenkman, Berger, Riley, Mann, & Hodge, 1990; Riley, Schenkman, Mann, & Hodge, 1991; Schenkman, Riley, & Pieper, 1996) have divided the STS movement into four phases: (1) Flexion-momentum Phase, which begins at movement initiation and continues until just before the buttocks lift off from the seat; (2) Momentum-transfer Phase, which begins at lift-off from the chair and continues until maximum dorsiflexion of the ankle is reached; (3) Extension Phase, which begins just after maximum dorsiflexion of the ankle is reached and continues until the hips first cease to extend; and (4) Stabilization Phase, which begins just after the hips cease to extend and continues until all motion associated with stabilization from rising is completed.

Naumann, Ziv, and Rang (1982) defined the STS in a similar fashion to Schenkman, et al.: (1) Flexion Phase, from the start of movement until lift-off; (2) Buttocks-off Phase, from lift-off until the cessation of flexion; and (3) Extension Phase, from the cessation of flexion until stability is reached in a standing position.

Rodosky, Andriacchi, and Andersson (1989) divided the movement into two phases, (1) Forward-thrust Phase, from initiation of movement until maximum dorsiflexion of the ankle, and (2) Extension Phase, from just after maximum dorsiflexion of the ankle until a standing position is reached.

Kralj, Jaeger, and Munih (1990) divided the STS movement into four phases. What is interesting in their approach is a more detailed breakdown of what is occurring while the buttocks are still in contact with the seat. (1) Initiation Phase was defined as being from the initiation of movement until the point at which the vertical ground reaction force begins to change in a positive direction (i.e., loading at the feet begins), (2) Seat-unloading Phase, from the end of the first phase until lift-off, (3) Ascending Phase, from lift-off until the knees were fully extended, and (4) Stabilization Phase, defined in an identical manner to Schenkman and colleagues.

Alexander, Schultz, and colleagues (Alexander, Schultz, & Warwick, 1991; Schultz, Alexander, & Ashton-Miller, 1992) have broken the STS movement down into two primary phases: (1) Phase I, from quiet sitting until maximum anterior head displacement and (2) Phase II, from maximum anterior head displacement until upright stance.

Millington, Myklebust, and Shambes (1992) divided the movement in three phases: (1) Weight-shift, from first discernible trunk flexion until start of the extension of the knees; (2) Transition, from the end of the first phase until the trunk flexion ceases; and (3) Lift, from the initiation of trunk extension until the last discernible trunk extension at full stance.

Kotake, Dohi, Kajiwara, Sumi, Koyama, and Miura (1993) divided the STS into six stages, each with a particular indicator: (1) Stage 1, subject is seated quietly; (2) Stage 2, commencement of trunk flexion and buttocks leave chair; (3) Stage 3, hip joints reach maximum flexion; (4) Stage 4, ankle joints reach maximum dorsiflexion; (5) Stage 5, standing; (6), Stage 6, stabilization in standing position.

Roebroeck, Doorenbosch, Harlaar, Jacobs, and Lankhorst (1994), used patterns of horizontal and vertical velocity of the body's center of gravity to define three phases: (1) Acceleration Phase, begins with movement onset and ends when maximal horizontal velocity of the center of gravity is reached; (2) Transition Phase, begins at maximal horizontal velocity of the center of gravity and ends when maximal vertical velocity of the center of gravity is reached; and (3) Deceleration Phase, begins with maximal vertical velocity and continues until the end of the movement.

Shepherd and colleagues (Shepherd & Gentile, 1994; Shepherd & Koh, 1996) simply divided the STS into two phases, a Pre-extension Phase and an Extension Phase. The dividing point between these two phases was lift-off from the seat.

Baer and Ashburn (1995) identified six points that can be used to divide the STS into three phases: Point 1 corresponds to quiet sitting and defined as 0.1 second prior to movement initiation, Point 2 to movement initiation, Point 3 to seat-off, Point 4 to mid stance when vertical acceleration changes to deceleration, Point 5 to upright stance, and Point 6 to quiet standing 1 second after achieving upright stance. Based on these points, the STS can be divided into three phases: from Point 2 to Point 3, from Point 3 to Point 4, and from Point 4 to Point 5. (Note that Baer and Ashburn did not explicitly define these three phases; they have been inferred from the definition of the points.) Other authors have either not divided the STS into clearly defined phases or have applied the phase definitions of other authors.

*Commonalities Among Various Phase Descriptions and Rationale for Phase Descriptions Employed in the Present Study*

Despite the variety of ways employed in dividing the STS movement into phases, and in defining these phases, it appears that a modification of the method of Schenkman, et al. (1990) is the best candidate for a standard division of the STS movement into its component parts. First, it is one of the few methods that has appeared in more than one published study, and the one of the few to be employed by a different group of authors (e.g., Lou, Chou, Chou, Lin, Chen, & Su, 2001; Vander Linden, Brunt, & McCulloch, 1994). Second, the events which define the different phases are clearly identifiable and can be measured directly, even without kinetic data. This is not the case with the method of Kralj, et al. (1990) which relies on kinetic data for defining the first phase, or that of Roebroeck, et al. (1994) which relies on the velocity of the body's center of gravity, a quantity that is derived from a temporal series of recorded distances. Third, most of the phases used by other investigators can be adapted to fit the scheme of Schenkman and colleagues (see Table 1). For these reasons, the method of Schenkman, et al. (1990) was used in the present study, with the following modification: Phase IV, Stabilization Phase, is called the Transition Phase. It is defined as the period from complete extension of the hips until all motion associated with stabilization from rising is completed, if the individual intends to remain standing, or until a subsequent movement pattern, such as walking, is initiated. This dual description is employed because although most previous

**Table 1.** Phases of the sit-to-stand movement used by various authors compared to those of Schenkman, et al. (1990).

| Schenkman, et al. (1990) | Phase I | Phase II | Phase III | Phase IV |
|---|---|---|---|---|
| Alexander, et al. (1991) | Phase 1 ----------------------> | | Phase 2 | |
| Kotake, et al. (1993) | Stage 2 | Stages 3 & 4 | Stage 5 | Stage 6 |
| Kralj, et al. (1990) | Phases 1 & 2 | Phase 3 ----------------------> | | Phase 4 |
| Millington, et al. (1992) | Phase 1 | Phases 1 & 2 | Phase 3 | |
| Naumann, et al. (1982) | Phase 1 | Phase 2 | Phase 3 | |
| Rodosky, et al. (1989) | Phase 1 ----------------------> | | Phase 2 | |
| Roebroeck, et al. (1994) | Phase 1 | Phase 2 | Phase 3 | |
| Shepherd & Gentile (1994) | Phase 1 | Phase 2 ----------------------> | | |

studies had the subject remain standing after completing the STS movement, more often in daily living the STS is a necessary precursor to locomotion. Furthermore, it is difficult for young children to stand still after completing the STS movement. Thus this final phase is often unpredictable.

*Strategies Employed in the Sit-to-Stand Movement*

Two primary strategies have been suggested for the execution of the sit-to-stand movement (Berger, Riley, Mann, & Hodge, 1988; Hughes, Weiner, Schenkman, Long, & Studenski, 1994; Schenkman, et al., 1990); the specific terms are from Hughes, et al. (1994): (1) "momentum transfer," in which hip and trunk flexion are used to generate momentum which can then be transferred to the whole body, and (2) "stabilization," in which trunk flexion is not used to generate momentum but rather to position the center of gravity of the body closer to the base of support at the time of seat-off; in this strategy the feet are also usually brought closer to the chair, thus making it easier to bring the center of gravity closer to the base of support. The momentum transfer strategy is also characterized by the center of gravity of the body being located behind the center of pressure (in some cases this may also be behind the base of support) at the time of seat-off, a relatively greater amount of trunk and hip flexion, a relatively greater hip flexion velocity, and a relatively greater hip joint moment but smaller knee joint moment.

On the other hand, the stabilization strategy is characterized by the center of gravity being located close to the base of support at the time of seat-off, a relatively smaller amount of trunk and hip flexion, a relatively smaller hip flexion velocity, and a relatively smaller hip joint moment but greater knee joint moment. Of course, these two strategies are not mutually exclusive: forward flexion might act both to move the center of gravity closer to the base of support as well as generate momentum (Hughes, et al, 1994, called this the "combined" strategy). Which of these strategies is employed seems to be dependent on the individual's functional ability, and is influenced especially by strength and balance. Hence the stabilization strategy is used more by older adults and other individuals with functional limitations (see the discussion below on "Special Populations"), while the momentum transfer strategy is used by younger adults and/or persons without functional limitations.

*Fundamental Mechanics of the Sit-to-Stand Movement*

When describing the fundamental mechanics of the STS movement, the modification of the phases of Schenkman, et al. (1990) described earlier will be used, with results from other authors being applied to Schenkman and colleagues (1990) scheme as much as this is possible (see Table 1). In addition, the discussion will assume that the momentum transfer strategy (Hughes, et al., 1994) is being used, as this appears to be the typical strategy used by non-functionally-impaired individuals. One difficulty encountered when trying to compare results between studies, aside from that of different phase descriptions being used, is that most studies restrict the use of the arms during the movement—usually by requiring the subject to fold the arms flat across the chest and not move the arms away from the chest during the movement—but some do not.

*Phase I: Flexion-momentum Phase*. Recall that the Flexion-momentum Phase begins with the initiation of movement and continues until just before lift-off from the seat. The movement is initiated by flexion of the hips brought about by a slight flexion moment. The remaining hip flexion proceeds as a result of gravitational action and momentum, with an eccentric hip extensor moment to control the hip flexion. This is followed, near the end of the phase, by slight flexion of the trunk (Kelley, et al., 1976; Kralj, et al., 1990; Kotake, et al., 1993). During this phase, the trunk flexes an average of 16°, and reaches maximum flexion in the early part of Phase II (Schenkman, et al., 1990). In addition, during Phase I, maxima are reached for hip flexion angular velocity, trunk flexion angular velocity, and neck extension angular velocity (Schenkman, 1990). The center of gravity of the body travels forward and slightly inferiorly during this phase, with the horizontal velocity component of the center of gravity reaching its peak at the end of the phase (Roebroeck, et al., 1994; Riley, et al., 1991). While the hip, knee, and ankle joints all contribute to the forward motion of the center of gravity during this phase as well as in Phase II, the greatest contributors appear to be the hip and ankle joints (Yu, Holly-Crichlow, Brichta, Reeves, Zablotny, & Nawoczenski, 2000). The propulsive impulse necessary for this phase is generated by a posteriorly-directed ground reaction force at the buttocks, followed (possibly; see Discussion section) by a smaller posteriorly-directed ground reaction force at the feet (Hirshfeld, Thorsteinsdottir, & Olsson, 1999; Magnan, McFadyen, & St-Vincent, 1996; Pai, Naughton, Chang, & Rogers, 1994).

*Phase II: Momentum-transfer Phase*. The Momentum-transfer Phase begins with lift-off of the buttocks (i.e., seat-off) and continues until maximum dorsiflexion of the ankle is reached (i.e., the cessation of all lower body flexion). During this phase, the horizontal linear momentum of the upper body generated during Phase I is transferred to the thigh segments and contributes to total body anterior movement (Pai & Rogers, 1991a; Riley, et al., 1991; Shepherd & Gentile, 1994; Schenkman, et al., 1990). Pai and

Rogers (1991a) and Roebroeck, et al. (1994) found that the major contributor to horizontal linear momentum is the upper body, while that to vertical linear momentum is the thighs, suggesting that although the upper body horizontal linear momentum may be transferred to the horizontal linear momentum of the thighs, the thighs are the major contributing segments to the vertical linear momentum of the whole body. This result argues against the interpretation of Riley, et al. (1991), who suggested that the upper body is the major contributing segment to both horizontal and vertical linear momentum, and that the horizontal momentum of the upper body was somehow transferred to the vertical momentum of the upper body. It appears, rather, that the horizontal linear momentum of the upper body generated by flexion of the trunk and hips is transferred to the thighs just after lift-off, while the thighs are primarily responsible for the vertical linear momentum of the whole body. The transfer of horizontal linear momentum from the upper body to the thighs has the result of potentially reducing the required lower limb muscle force (Shepherd & Gentile, 1994).

In this phase the propulsive impulse at the feet changes to a braking impulse generated by an anteriorly-directed ground reaction force. This braking impulse serves to slow the forward velocity and momentum of the body. In addition, there is a vertical ground reaction force at the feet that generates a vertical propulsive impulse and vertical velocity of the center of gravity (Hirschfeld, et al., 1999; Pai, et al., 1994; Pai & Rogers, 1990).

Several maxima are reached during Phase II: Maximum flexion of the hip, followed by maximum trunk flexion, then maximum extension of the neck, and finally maximum dorsiflexion of the ankle (Schenkman, et al., 1990). The hip extension moment, which had been controlling flexion of the hips, reaches a maximum just after lift-off, as does the knee extension moment, which must limit the flexion of the knee following transfer of weight bearing from the buttocks and feet entirely to the feet. These events coincide with near-maximum flexion of the hip and knee (Kelley, 1976; Schenkman, et al., 1990).

The peak hip extension moment for an adult male of average stature and body mass (175 cm and 70 kg, respectively) is approximately 40 to 60 Nm (Fleckenstein, Kirby, & MacLeod, 1988; Pai & Rogers, 1991b), while the average peak knee extension moment for the same individual is approximately 150 Nm (Pai & Rogers, 1991b). The actual peak hip and knee extension moments will, of course, vary depending upon an individual subject's stature and body mass.

Kotake, et al. (1993) calculated that the minimum hip extension moment required to complete the STS would be 0.7±0.1 Nm per kilogram of body weight (kg BW) and the minimum knee extension moment would be 0.9±0.1 Nm/kg BW for the subjects in their study, which were all of similar stature. For a 70 kg individual (assuming that his or her anthropometric measures were similar to those of the subjects employed by Kotake, et al.), this would equate to a peak hip extension moment of 49 Nm and a peak knee extension moment of 63 Nm. The former value is well within the range of the values reported in the literature (Fleckenstein, Kirby, & MacLeod, 1988; Pai & Rogers, 1991b), whereas the latter value is much lower than that reported by Pai and Rogers (1991b). The reason why individuals produce knee extension moments two to three times greater than those required to successfully complete the STS is not clear, although restrictions imposed in experimental settings may require greater torque to be exerted.

During Phase II, the center of gravity continues to travel forward and upward, reaching its maximum anterior travel by the end of the phase (Schenkman, et al., 1990). Also, at the end of the phase, the vertical component of the velocity of the center of gravity reaches its peak (Roebroeck, et al., 1994; Riley, et al., 1991). At the start of Phase II, the body is in dynamic stability, as the center of gravity is approximately 7 cm behind the center of pressure, which is located beneath the heels, at lift-off. At the end of the phase, however, the horizontal position of the center of gravity is close to the that of the center of pressure, indicating a quasi-static balance situation (Kelly, et al., 1976; Murray, Seireg, & Scholz, 1967; Pai, et al., 1994; Riley, et al., 1991; Schenkman, et al., 1990).

*Phase III: Extension Phase.* The Extension Phase begins just after maximum dorsiflexion of the ankle is reached and continues to the end of hip extension (i.e., when hip angular velocity first reaches 0°/s). Although the hip, knee, and ankle joints all contribute to the vertical motion of the center of gravity during this phase, the greatest contributors appear to be the knee and hip joints (Yu, et al., 2000). In this phase, hip, trunk, and knee extension angular velocities reach their maxima, and then decrease to near 0°/s at the end of the phase (Schenkman, et al., 1990).

During Phase III, the center of gravity continues to move upward and reaches its maximum height by the end of the phase. As at the end of Phase II, the horizontal position of the center of gravity nearly coincides with that of the center of pressure (which is now located just anterior to the ankles), indicating a quasi-static balance situation (Kelly, et al., 1976; Murray, et al., 1967; Pai, et al., 1994; Riley, et al., 1991; Schenkman, et al., 1990).

*Phase IV: The Transition Phase*. The fourth phase, the Transition Phase, is defined as beginning just after extension of the hip ceases and continuing until all motion associated with stabilization from rising is completed, if the individual intends to remain standing, or until a subsequent movement pattern, such as walking, is initiated. In cases where the individual intends to remain standing, it is difficult to determine the end of Phase IV, as the motion due to stabilization is often indistinguishable from normal postural sway which occurs during normal stance. Although this situation has not been studied as an aspect of the STS movement, the mechanics of Phase IV are likely to be similar to those encountered during postural sway, where perturbations of the body's center of gravity toward the edge of body's base of support are countered by activation of the body's postural muscles, especially those associated with the ankle joint (Woollacott, 1986).

In situations where a subsequent movement (i.e., gait) is to be initiated, as is usually the case when rising from a seated position, it is also difficult to determine when the end of Phase IV occurs and when the subsequent movement begins (see below in the section "Sit-to-Walk Movement").

*Muscular activity during the STS movement.* Goulart and Valls-Sole (1999) suggest that the lumbar paraspinal (i.e., erector) muscles, quadriceps muscles, and hamstring muscles are the prime movers for the STS movement, and are activated in the order listed. They suggest that the activation of the lumbar paraspinals are used to straighten the trunk prior to movement initiation, that the quadriceps (at least the rectus femoris) are involved in the initial hip flexion and in later knee extension, and that the hamstrings are involved in hip extension during the extension phase of the movement. On the other hand, they argue that the tibialis anterior and abdominal muscles serve as postural muscles that act to make any necessary postural adjustments, as opposed to being prime movers in the actual execution of the movement.

## *Variables Affecting the Mechanics of the Sit-to-Stand Movement*

### *Use of the Arms*

Few studies have investigated the use of the arms in the performance of the STS movement, despite the fact that arm movement of some kind occurs naturally in performing the STS (Carr & Gentile, 1994). When the arms are used, they tend to be used in one of two ways: Either pushing against the arm rests (if available) or seat of the chair in order to facilitate the movement, or by being thrust forward along with the trunk in order to increase forward momentum. Both types of arm movements have been investigated, albeit by few studies.

Several studies have investigated the effects of arm rests. Burdett, Habasevich, Pisciotta, and Simon (1985), explicitly studied the effects of using the arms to assist in performing the STS movement by pushing against arm rests versus using the legs only. The authors found no significant difference in maximum hip, knee, or ankle flexion between the arm and no-arm condition for a group of healthy, young adult subjects. However, there was a significant difference in the peak hip extension moment, as well as in the peak knee extension moment, between the two conditions, both variables being greater for the no-arm condition. Arborelius, Wretenberg, and Lindberg (1992) found similar results: the use of arm rests decreased the maximum hip moment by about 50% and decreased the maximum knee moment by about 30%. In addition, the subjects in

Arborelius, et al.'s study rated the STS as being easier (8.00 vs. 8.55 on the Borg scale of effort) when the arms were used. Furthermore, Ellis, Seedhom, and Wright (1984) found a reduction in the tibio-femoral vertical force of 18 to 21%. In using the arms to assist the STS, the joints of the upper extremity (shoulder and elbow) are now generating extension moments, thereby decreasing the moments required of the hip and knee joints. To this end Anglin & Wyss (2000) investigated the arm motion and hand loads encountered when using arm rests, without respect to motion of the lower extremity, and found that the average peak hand load was 134 N, or 19% body weight; a similar result was found by Alexander, et al. (1991) for older adults.

Carr and Gentile (1994) investigated the other possible use of the arms: thrusting the arms forward with the trunk at the beginning of the movement. In their study, subjects were asked to perform the STS movement both in a preferred manner, where the arms could be thrust forward, and in a restricted manner, in which subjects were required to keep the elbows flexed at 90° and the arms at their sides. The authors found no significant difference between the two conditions in the amplitude of trunk flexion, horizontal and vertical momentum of the center of gravity, maximal hip and knee joint moments, and maximum support moment (a net extensor moment generated by the hip, knee, and ankle). However, differences did exist between the two conditions in terms of the duration of the maximum support moment, defined as the normalized length of time that the support moment equaled or exceeded three times body weight, with the restricted condition having a significantly longer duration. Thus lack of arm use, while not requiring an increase in the maximum support moment (i.e., the hip and knee joint moments), requires this maximum support moment to be sustained for longer periods.

Shepherd and Gentile (1994) argue that a brief extension moment (versus the distribution of a moment of the same magnitude over a longer period of time) may be more efficient and lead to less muscle fatigue. In other words, even though the body has the ability to compensate for restricted arm use and does not require an increase in the maximum support moment, use of the arms makes the performance of the STS movement more efficient by reducing the required duration of the maximum support moment.

*Speed of Ascent*

Before discussing those studies that investigated the effects of speed of ascent on the mechanics of the STS movement, it is important to note that most studies on the STS made no attempt to control speed, but rather allowed the subjects to select a preferred speed. Shepherd and Gentile (1994) have noted that even when speed of ascent is not controlled, movement times for the STS remain fairly consistent, and typically range from 1.2 to 2 seconds. However, it is clear that initial position has an effect on speed of ascent, and that variations in speed of ascent affect the mechanics of the STS movement.

Pai, Rogers, and colleagues (Pai, et al., 1994; Pai & Rogers, 1990, 1991b) have conducted three studies on the effects of speed of ascent on the mechanics of the STS movement. In all three studies, the authors allowed subjects to perform the STS at three self-selected speeds: slow, normal, and fast. Across the three speeds, no significant differences were found in the joint angle profiles of the hip, knee, and ankle, nor in the hip extensor moment or ankle plantar flexion moment. Significant differences were found, however, for the hip flexion moment between the slow and fast speeds (greater for the fast speed), for the knee extension moment across all speeds (increased moment with increasing speed), and for the dorsiflexion of the ankle moment between the fast and slow speeds and between the fast and normal speeds (in both cases greater for the fast speed; Pai & Rogers, 1991b). Other significant differences between speeds included a decrease in the time to peak vertical center of gravity velocity with increasing speed and an increase in peak vertical momentum with increasing speed. In contrast, the peak horizontal momentum did not change significantly with increasing speed of ascent (Pai, et al., 1994; Pai & Rogers, 1990). Similar results were obtained by Vander Linden and colleagues (1994), who found no significant differences in joint angles from normal to fast speeds, but did find a significantly smaller time to peak force and a significantly greater peak force for the fast speed (115 vs. 120% BW). In other words, performing the STS more quickly requires greater joint moments (and ground reaction forces) in order to accelerate the body more quickly and achieve a faster rise time. The increased velocity of the STS from slow to fast speeds also accounts for the increase in peak momentum and time to peak center of gravity velocity.

*Initial Position*

One of the difficulties encountered when investigating the STS movement is that a variety of initial positions were used (see Table 2). Some studies make an effort to control the initial position of the movement, usually by fixing the seat height at a certain percentage of knee height, and by fixing the knee angle at 90°. However, these initial positions are not universal, and therefore comparison between studies is difficult due to the variations in initial position. Several researchers have explicitly studied the effects of initial position on the performance of the STS. The two aspects of initial position

Table 2. Initial starting position used in studies of the sit-to-stand movement

| Study | Seat Height | Knee Angle | Ankle Angle |
|---|---|---|---|
| Alexander, et al. (1991) | Thighs parallel* | 70° of flexion | 20° dorsiflexion |
| Alexander, et al. (1996) | 60, 80, 100, 120, 140% kh† | ? | ? |
| Arborelius, et al. (1992) | 100% kh, kh+$^1/_3$ thigh length, kh+ $^2/_3$ thigh length | ? | ? |
| Burdett, et al. (1985) | 43 cm & 64 cm | ? | ? |
| Carr & Gentile (1994) | 110% of shank length (head of fibula to floor) | ? | ? |
| Doorenbosch, et al. (1994) | 100% kh | 105° flexion | ? |
| Fleckenstein, et al. (1988) | 44 cm | 75, 105° flexion | ? |
| Galli, et al. (2000) | ? | 110° flexion | ? |
| Ikeda, et al. (1991) | 80 % of kh | ? | 18° dorsiflexion |
| Jeng, et al. (1990) | 44 cm | ? | 10° dorsiflexion |

* Refers to the thighs being parallel to the ground.
† kh = knee height

**Table 2. (cont'd)**

| Study | Seat Height | Knee Angle | Ankle Angle |
|---|---|---|---|
| Kelley, et al. (1976) | Thighs parallel* | 75° flexion | ? |
| Lou, et al. (2001) | 65, 80, 100, 115% kh† | ? | ? |
| Millington, et al. (1992) | 43 cm | 90° flexion | ? |
| Munton, et al. (1984) | 42, 59.5 cm | ? | ? |
| Naumann, et al. (1982) | 30-150% kh | ? | ? |
| Pai & Rogers (1990, 1991a,b)<br>Pai & Lee (1994)<br>Pai, Naughton, et al. (1994) | 45 cm | 81° flexion | 22° dorsiflexion |
| Riley, et al. (1991) | 80% of kh | ? | 18° dorsiflexion |
| Rodosky, et al. (1989) | 65, 80, 100, 115% kh | ? | ? |
| Roebroeck, et al. (1994) | 100% kh | 105° flexion | ? |
| Schenkman, et al. (1990) | 80 % of kh | ? | 18° dorsiflexion |
| Schenkman, et al. (1996) | 65, 80, 100, 115% kh | ? | ? |

* Refers to the thighs being parallel to the ground.
† kh = knee height

**Table 2.** (cont'd)

| Study | Seat Height | Knee Angle | Ankle Angle |
|---|---|---|---|
| Schultz, et al. (1991) | Thighs parallel* | 70° of flexion | 20° dorsiflexion |
| Shepherd & Gentile (1994); Shepherd & Koh (1996) | 110% of shank length | ? | ? |
| Stevens, et al. (1989) | Thighs parallel | 90° flexion | 0° dorsiflexion |
| Su, et al., (1998) | 65, 80, 100, 115% kh† | ? | ? |
| Vander Linden, et al. (1994) | Thighs parallel | 72, 85° flexion | 18, 5° dorsiflexion |
| Wheeler, et al. (1985) | 44 cm | ? | ? |
| Yoshida, et al. (1983) | Thighs parallel | 90° flexion | 0° dorsiflexion |
| Yu, et al., (2000) | Thighs parallel | 90° flexion | ? |

* Refers to the thighs being parallel to the ground.
† kh = knee height

typically varied are the seat height and the knee and/or ankle angle (i.e., the position of the feet relative to the seat), although two studies have investigated the effects of initial trunk angle and trunk motion (Doorenbosch, Harlaar, Roebroeck, & Lankhorst, 1994;Shepherd & Gentile, 1994). Only the effects of initial knee/ankle angle and initial trunk angle will be discussed now; seat height and other variables related to chair design, such as arm rest position, use of seat backs, and seat angle will be discussed later.

Munton, Ellis, and Wright (1984) used electromyography (EMG) to investigate the effect of differences in seat height and initial knee position on muscle activity during the STS. Two seat heights, 42 and 59.5 cm, and two initial knee positions, "normal (knee joint at approximately 90° of flexion)" and "feet under chair (knee joint greater than 90° of flexion)," were used. The authors found no differences in muscle activation patterns between the two seat heights nor between the two initial knee joint positions. However, Stevens, Bojsen-Møller, and Soames (1989) found greater hamstring and quadriceps activity (increased firing rate) when subjects started in a "preferred (i.e., self-selected) position" versus a "standard (i.e., knee joint at 90° of flexion, ankle joint at 0° of dorsiflexion) position." The authors put forth no explanation as to why quadriceps and hamstring activity would be greater in the preferred condition, as one would expect the preferred condition to be more efficient than the standard condition.

Fleckenstein, et al. (1988) examined two initial knee joint angles, 75 and 105° of flexion. They found that the peak hip flexion angle, peak hip flexion moment impulse, peak hip extension moment, and the peak hip extension moment impulse were all significantly greater at an initial knee joint angle of 75°. In addition, the STS movement took 0.2 seconds longer to complete with the knee joint at an initial angle of 75°. The authors suggest that limiting the initial knee-flexion range requires greater trunk and hip flexion, as well as a higher hip flexion moment impulse, during Phase I, and therefore a greater hip extension moment is required during Phase II to control the hip flexion.

Vander Linden, et al. (1994), using initial ankle positions of 5 and 18° of dorsiflexion (95 and 108° of flexion of the knee, respectively), found that ankle and knee joint excursions were significantly greater at an initial ankle joint angle of 18° of dorsiflexion, whereas maximum horizontal velocity of the head was significantly greater at 5° of dorsiflexion. In addition, Phase II was significantly longer for the 5° of dorsiflexion condition, while Phase III was significantly shorter for the 5° of dorsiflexion condition. Vander Linden and colleagues reached a conclusion similar to Fleckenstein, et al (1988). Namely, with a limited initial knee-flexion range, greater forward momentum is required to be generated by the upper body (as evidenced by the greater maximal horizontal velocity of the head in the 5° of dorsiflexion position), and therefore a prolonged braking force (i.e., hip extension moment) is required during Phase II to control this forward momentum.

Shepherd and Koh (1996) investigated the effects of three different foot placements (and, therefore, three knee joint angles) on the STS movement: "feet back," with the feet placed such that the heels were aligned with the front legs of the chair (knee joint angle > 90° of flexion); "feet forward," with the shank perpendicular to the floor (corresponding to a knee joint angle of approximately 90° of flexion); and a preferred condition. The results of Shepherd and Koh's study confirmed those of Fleckenstein, et *al.* (1988) and Vander Linden, et al. (1994). Namely, as the feet were placed farther forward, movement time increased, due to the increased distance that the center of gravity must travel from the seat base of support to the feet base of support; and flexion of the hip, hip flexion velocity, and the peak hip moment all increased significantly as the feet were placed farther forward. In contrast, both the peak knee moment and the peak ankle moment decreased when the feet were placed farther forward.

The results of the aforementioned studies on initial position suggest that the optimal foot placement for the performance of the STS movement is such that the knees are flexed greater than 90°. When the feet are placed such that the knees are flexed less than 90°, the movement time increases, and, more importantly, the peak hip moment increases. Thus, when working with individuals who have hip joint pain or limited strength in the muscles surrounding the hip joint, it is important that the seating arrangement is such that they can flex their knees greater than 90° and simultaneously place their feet on the ground. It is interesting to note that in the study by Shepherd and Gentile (1994) the preferred condition of all of the subjects involved a foot placement in which the knees were flexed greater than 90°.

As noted above, two studies have investigated the effects of initial trunk position and trunk motion on the STS movement. Shepherd and Gentile (1994) studied the STS under three initial trunk conditions: erect sitting, trunk flexed, and trunk fully flexed. As might be expected, the initial trunk position had significant effects on the STS movement, especially at the hip joint. As the trunk position became more flexed, the amplitude of hip flexion, peak hip flexion velocity, and movement time all decreased. Furthermore, the onset of extension at the hip and knee joints was affected by the initial trunk position. Namely, as the trunk became more flexed, both joints began to extend earlier in the movement and closer to one another in time. In addition, in the fully flexed position, the knee began extending before the hip whereas in the other initial trunk positions the hip began extending before the knee. The peak moments for the hip, knee, and ankle joints were not significantly different across the three conditions. The same was true for the maximum support moment. However, the duration of the maximum support moment increased with increasing initial trunk flexion. This result led the authors to argue that a brief extension moment (versus the distribution of a moment of the same magnitude over a longer period of time) may be more efficient and lead to less muscle fatigue. In other words, even though the body has the ability to compensate for restricted hip motion, due to flexed initial trunk position, and does not require an increase in the maximum support moment, having the ability to fully flex the trunk during the movement itself makes the performance of the STS movement more efficient by reducing the required duration of the maximum support moment (i.e., the required support moment impulse). Recall that a similar result was obtained by Carr and Gentile (1994) when investigating arm motion.

The study of the effects of initial trunk position conducted by Doorenbosch, et al. (1994) differed from that of Shepherd and Gentile (1994) in that the two subject groups, natural and fully-flexed, started with a vertical trunk. While the natural group was instructed to rise in a natural, comfortable manner, the fully-flexed group was asked to flex the trunk as fully as possible before lift-off from the seat. Thus Doorenbosch, et al. were not so much investigating the effects of initial trunk position as they were investigating the effects of trunk flexion (i.e., motion) on the STS. It should also be noted that in their study, Doorenbosch, et al. controlled the speed of ascent, and this speed of ascent was the same for both conditions. Their results indicated no significant differences between the two conditions in the motion of the knee and ankle joints, though such a difference did exist for the hip joint, as might be expected. In the fully-flexed condition, the peak hip and ankle extension moments were greater, and the peak knee extension moment less, than in the natural condition. In addition, the peak hip and ankle extension moments occurred later, and the peak knee extension moment earlier, in the fully-flexed condition versus the natural condition. The authors hypothesized that the decrease in the peak knee extension moment in the fully-flexed condition was brought about by a change in the activity of the biarticular muscles that cross the knee joint (primarily a decrease in the activity of the rectus femoris). The authors conclude that performing the STS with full flexion is one strategy for those individuals with weak knee extensors. It may also be beneficial for those suffering from arthritis or other pain in the knee joint. However, the fact that the peak hip moment increased in the fully-flexed condition, would make this strategy undesirable for those individuals who have arthritis or other pain in the hip joint.

*Chair Design*

When considering the effects of chair design on the performance of the STS movement, there are several elements of that design that can be varied, including seat height, seat angle, seat depth and seat characteristics (such as foam or no foam); angle of the backrest (if used); and armrest position (if used). Of these elements, seat height has been most commonly studied. The effects of seat and backrest angle, seat characteristics, and armrest position have received some attention, while no attention has been given to seat depth.

As noted, the principal dimension altered in studies on the effect of chair design on the STS movement is seat height. All of the studies which compared differing seat heights found similar results. Burdett, et al. (1985) investigated two seat heights, 64 and 43 cm, the latter being considered a "standard height." The authors found a significantly greater peak hip extension moment, as well as a significantly greater peak knee extension moment, for the standard seat height. There were no significant differences in the peak ankle moments between the two seat heights. As might be expected, maximum hip and knee joint flexion were also significantly greater for the standard chair.

Rodosky, et al. (1989), who used seat heights of 65, 80, 100, and 115% of knee height, also found that with increasing seat height, maximum flexion at the hip, knee, and ankle significantly decreased. In addition, peak flexion moments of the hip and knee decreased significantly with increasing seat height, whereas there was no significant change in the peak ankle moment. Likewise, Schenkman, Riley, and Pieper (1996), using the same seat heights, found that maximum trunk flexion angular velocity, maximum hip extension angular velocity, maximum knee extension angular velocity, and maximum trunk extension angular velocity all decreased with increasing seat height.

Alexander, Koester, and Grunawaldt, (1996) also investigated the effects of seat height, using seat heights of 60, 80, 100, 120, and 150% of knee height, similar to those used by Rodosky, et al. (1989). Alexander, et al. (1996; confirmed by Alexander, et al., 2000) found a decrease in rise time with increasing seat height, as well as a decrease in maximum flexion of the hip with increasing seat height. Similarly, Arborelius, et al. (1992) found a reduction in the peak hip moment by 50% for a high-stand stool (knee height plus 2/3 thigh length) versus an ordinary chair (knee height), and a reduction in the peak knee moment of 60% for the high-stand stool. Ellis, et al. (1984) also found a 33%

reduction in the tibio-femoral force for a high chair versus a low chair (the height of each type of chair was not defined).

Aboresius, et al. (1992) and Alexander, et al. (1996) also had subjects self-report ratings of perceived effort or difficulty for the different seat heights, and found that perceived effort and difficulty significantly decreased with increasing seat height. The results of these studies suggest that increasing the seat height reduces the peak extension and flexion moments about the knee and hip, as well as reducing the maximum flexion of the hip and knee joints required for the movement, thereby decreasing the difficulty of the movement, especially for special populations. However, Arboresius, et al. note that the percentage of body weight supported by the seat of the stool or chair significantly decreases as the seat height increases. Therefore, a higher seat height places a greater load on the legs, and would not be the best choice for prolonged periods of sitting.

In addition to studying the effects of seat height, Alexander, et al. (1996) also investigated the effects of three other chair design variables: backrest recline/seat tilt (95° recline/0° tilt; 105° recline/10° backward tilt; 115° recline/20° backward tilt), foam vs. no-foam seat, and armrest position (low, forward, standard). Increasing the backrest recline/seat tilt led to an increase in rise time, an increase in maximum flexion of the hip, and an increase in the difficulty rating. The presence of foam on the seat also increased rise time, maximum flexion of the hip, and the difficulty rating. These results were especially true for the older adults in the study. On the other hand, the arm rest position had little effect on rise time, flexion of the hip, or degree of difficulty for both younger and older adults. These results confirm anecdotal evidence that a greater recline and/or softer seat make rising more difficult. However, for individuals who must sit for long

periods, it seems that a happy medium between sitting comfort and ease in rising must be reached.

### *Special Populations*

Variations that occur in the sit-to-stand movement in different populations as compared to the "norm," which is invariably the pattern, mechanics, etc. of the sit-to-stand movement in younger adult subjects, are discussed in this section. Note that although children would constitute a "special population" relative to younger adults, the STS movement in children is discussed in more detail in a subsequent section.

*Older adults.* When looking at age as a variable affecting the STS movement, researchers almost exclusively focus on the older adult population. This is due to the fact that motor function often declines with increasing age (Shepherd, 1987), and that this decline in motor function may challenge successful performance of the STS movement. Though many studies define "older adult" as anyone over 65 years of age, the actual mean age and age-range of older adult subjects in these studies varies considerably. The mean age and age-range of older adults used in various studies is shown in Table 3. A further difficulty when studying older adults is variation in physical condition, although many studies recruit only subjects that are able to perform the STS and who are free from severe arthritis or other diseases.

One variable of interest when comparing older and younger adult subjects on the STS movement is the total time required to complete the movement (rise time). The hypothesis is that just as movement time in other motor skills tends to increase with age after about 40 years (Shephard, 1987), so to will rise time. Yoshida, Iwakura, and Inoue

**Table 3.** Age range and mean age of older adult subjects used in studies of the sit-to-stand movement.

| Study | N | Mean Age (yrs.) | Age Range (yrs.) |
|---|---|---|---|
| Alexander, et al. (1991) & Schultz, et al. (1992) | | | |
| Group A | 23 | 72.1 | 63 - 86 |
| Group B | 11 | 84.4 | 75 - 92 |
| Alexander, et al. (1996) | 29 | 84.0 | 73 - 93 |
| Baer, et al. (1995) | 30 | 61.6 | 50 - 80 |
| Hughes, et al. (1994) | 22 | 72.0 | 64 - 105 |
| Hughes, et al. (1996) | 11 | 78.0 | ? - ? |
| Ikeda, et al. (1991) | 9 | 66.9 | 61 - 74 |
| Millington, et al. (1992) | 10 | 69.0 | 65 - 76 |
| Mourey, et al. (2000) | 7 | 75.1 | 71 - 82 |
| Papa & Cappozzo (2000) | 35 | ? | 65 - 81 |
| Vander Linden, et al. (1994) | 8 | 68.8 | 61 - 78 |
| Wheeler, et al. (1985) | 10 | 75.0 | 65 - 81 |
| Yoshida, et al. (1983) | 20 | 63.7 | ? - ? |

(1983) found that older adults took significantly longer to perform the STS, a result supported by Alexander, et al. (1996) and Mourey, Grishin, d'Athis, Pozzo, and Stapley (2000). However, Alexander, et al. (1991) found that there was no significant difference in rise time when arms were used to assist in the STS between younger adults and older adults who were able to rise without using their arms ("Old Able" group), while there was a significant difference in rise time when arms were used between the Old Able group and the older adults who were unable to rise without the use of their arms. There was also a difference, though not significant, between the Old Able group and the younger adults in rise time when the arms were not used (longer rise time for the Old Able group). Similarly, Wheeler, Woodward, Ucovich, Perry, and Walker (1985) found that older adults took longer to rise than younger adults, though this difference was not significant. It is interesting to note that as the difficulty of the STS movement increases due to changes in the initial position, such as having the feet placed farther in front of the body, and chair design, especially decreasing chair height, the differences between younger adults and older adults in rise time also increases (Alexander, et al., 1991, 1996, 2000). Thus it appears that when the difficulty of the STS task is low, such as when the arms are used and/or the chair height is relatively high (about 115% of knee height), younger adults and older adults are similar in terms of rise time. However, as the difficulty of the STS task increases, older adults take progressively longer than the young adults to perform the STS movement.

As far as joint motion is concerned, Baer and Ashburn (1995) found that healthy older adults exhibited only a small amount of trunk rotation and lateral flexion, which is consistent with younger adults. Wheeler, et al. (1985) found older adults to have significantly greater trunk flexion during the STS movement than the younger adults, but found no significant difference between the groups in maximum flexion of the knee. Papa and Cappozzo (2000) also found older adults to have a significantly greater trunk flexion during the STS movement than younger adults. Alexander, et al. (1991) found that in the without-arms condition, older adults had significantly greater flexion of the trunk, hip, and knee joints than the younger adults, whereas in the with-arms conditions, the older adults only differed from the younger adults in maximum flexion of the hip. All of the above-mentioned authors suggest that the greater trunk flexion seen in older adults is an attempt to bring the body's center of gravity closer to the base of support at the time of seat-off. However, Ikeda, et al. (1991) found no significant differences between younger and older adults in maximum trunk, hip, knee, or ankle flexion when the subjects performed the STS without using the arms. In addition, studies involving other populations that used the stabilization strategy (in which the goal is to bring the center of gravity closer to the base of support; Hughes, et al., 1994) found that the amount of trunk and hip flexion was actually less than when the momentum transfer strategy was used (Galli, Crivellini, Sibella, Montesano, Bertocco, & Parisio, 2000; Lou, et al, 2001). Therefore it is possible that the older adult subjects in the studies by Wheeler, et al., Papa and Cappozzo, and Alexander, et al. may actually be using the momentum transfer strategy but must generate greater momentum to compensate for lower extremity muscle weakness.

The horizontal component of the velocity of the center of gravity in younger versus older adults during the STS movement was examined by Mourey, et al. (2000). They studied the STS movement under two different vision conditions (normal and blindfolded) combined with two different speed conditions (normal and fast). The authors found that the peak horizontal velocity of the center of gravity and the horizontal velocity of the center of gravity at seat-off were both significantly lower for the older adult subjects versus the younger adults across all conditions, with the difference being magnified in the blindfolded condition (thus stressing the importance of visual cues for the older adults). This would seem to be suggest that subjects in this study were using a form of the stabilization strategy (Hughes, et al., 1994).

Although joint angular velocities would also be of interest when investigating the effect of age on the STS, few studies report this information. One such study was that by Ikeda, et al. (1991). In this study, older adults had greater trunk flexion and knee extension velocities, and smaller hip flexion, neck extension, hip extension, neck flexion, and trunk extension velocities than younger adults, although none of these differences were significant. Papa & Cappozzo (2000), on the other hand, did find older adults to have a significantly greater trunk flexion velocity versus younger adults. They suggest that the greater trunk flexion velocities seen in older adults is used to generate more forward momentum to be transferred to the extension phase of the movement (assuming they are using the momentum transfer strategy; Hughes, et al., 1994).

Similarly, few studies investigated kinetic differences in the STS between younger and older adults. Ikeda, et al. (1991) found that older adults had a greater normalized (divided by body weight times height) maximum knee torque and a smaller normalized maximum hip torque than younger adults. However, neither of these differences were significant. Schultz, et al. (1992) used a biomechanical model to calculate the joint torques required to perform the STS for both younger and older adults using data from

Alexander, et al. (1991). The differences in the required torques between the groups was small, with the only significant difference being for the ankle joint. More important, however, was the fact that the required joint torques for the older adults were all less than the maximum joint torque strengths reported in the literature (Borges, 1983; Markhede & Grimby, 1988), leading the authors to conclude that physical strength is not the limiting factor in older adults' ability to perform the STS. They suggest that postural stability and balance is more of a factor in limiting STS performance. On the other hand, Hughes, Myers, and Schenkman (1996) found that a group of functionally-impaired (defined as having to use a railing when descending stairs and the inability to rise from a 33 cm chair) older adults required a knee moment that was 78% of their available strength to rise from a chair set at knee height versus 34% for younger adults. This difference may reflect, in part, the use of the stabilization strategy (Hughes, et al., 1994) which results in a relatively greater knee joint moment. They concluded that while this required joint torque is less than the older adults' available strength, and while balance and postural stability may be important, strengthening exercises may help improve STS function; this conclusion is echoed by Riley, Krebs, and Popat (1997) in an analysis of sit-to-stand failure. However, several studies that employed a strength-training protocol with older adults and studied changes in the performance of the STS movement (usually by noting the time taken to successfully complete a certain number of repetitions of sitting-down and rising-up, or by the number of successful rises) found no differences between pre- and post-testing between trained subjects and controls (Judge, Whipple, & Wolfson, 1994; Schlicht, Camaione, & Owen, 2001; Singh, Clements, & Fiatarone, 1997).

The results of those studies which compared older and younger adults in the STS suggest that only small differences exist between the two groups in most kinematic and kinetic parameters, the main exceptions being rise time, where older adults take longer to rise than younger adults, especially as the difficulty of the STS task increases. The increase in rise time with increasing age and with increasing task difficulty seen in most older adults, would seem to fit the hypothesis that it is balance that limits STS performance in older adults. In other words, older adults move their feet back toward the chair (thus moving the base of support backward) and flex the trunk in order to place the center of gravity of the body closer to the base of support at the time of seat-off (i.e, the stabilization strategy); all of these postural adjustments require a greater movement time (Alexander, et al., 1996; Hughes, et al., 1994; Schultz, et al., 1992). On the other hand, the greater amount of trunk and hip flexion seen in the studies by Wheeler, et al. (1985), Papa and Cappozzo (2000), and Alexander, et al. (1991) suggests that some older adults use the momentum transfer strategy or a combination of the two strategies. This would be consistent with the results found by Hughes, et al. (1994), in which out of 20 older adult subjects 11 used the momentum transfer strategy, 4 used the stabilization strategy, and 5 used a combination of the two.

*Pregnant women.* Lou, et al. (2001) investigated the kinematics and kinetics of the STS movement at different stages of pregnancy. The authors found that overall (four different chair heights were actually used; see Table 2) the total movement time increased from the first through the third trimesters of pregnancy; that the peak hip flexion angle decreased, while the peak knee flexion angle remained unchanged, from the first and second trimesters to the third trimester; and that the peak hip flexion moment decreased, but the peak knee moment increased, from the first through the third trimesters. These results are likely due to the increased size of the abdomen, especially during the last trimester, which changes the body's center of gravity and increases the overall load on the body and especially on the lumbar spine. Decreasing the amount of hip flexion decreases the hip flexion moment (and presumably that at the lower back), as does increasing the movement time (i.e., decreasing the hip flexion velocity), but consequently leads to a greater knee joint moment.

*Obese adults.* Not surprisingly, obese subjects exhibit a STS movement pattern similar to that observed in third-trimester pregnant women: A smaller amount of hip flexion leading to a smaller peak hip joint moment, thus protecting the lower back (yet see below in the section on adults with disabilities), but resulting in a larger knee joint moment (Galli, et al., 2000).

*Adults with disabilities.* Individuals in this category fall into one of two general categories: those whose disabilities result from chronic pain, such as lower back pain and arthritis, and those whose disabilities result from neurological impairment, including stroke (including resulting hemiparesis) and other neurological disorders.

Coghlin and McFadyen (1994) compared the performance of the STS movement of individuals with lower back pain to that of healthy individuals. The authors anticipated finding results similar to those which were subsequently found for pregnant women and obese subjects; namely, that the low back pain subjects would choose a strategy that would minimize hip flexion and the hip flexion moment, thereby minimizing the stress on the lower back, but at the same time increase the moment at the knee. However, they found that while some low back pain subjects exhibited this pattern, others employed the strategy of a greater hip flexion and hip moment, but a smaller knee joint moment. The authors concluded, therefore, that low back pain subjects do not choose one clear strategy when performing the STS task.

In one early study on the effects of arthritis on the STS movement, Munton, et al. (1984) found no differences in the electromyography patterns of the muscles of the lower extremities between arthritic and "normal" subjects. A more recent study by Munro, Steele, Bashford, Ryan, and Britten (1998) found that older adult subjects with rheumatoid arthritis had longer movement times than those reported in the literature for non-arthritic older adults. Furthermore, the arthritic subjects had lower net knee moments at seat-off compared to those reported in the literature. Munro, et al. suggested that this latter result may indicate a choice of the momentum transfer strategy (Hughes, et al., 1994) so as to avoid large moments at the knee and minimize knee joint pain. However, the longer movement times of the arthritic subjects is suggestive of the stabilization strategy (Hughes, 1994). It may be that older adults with arthritis use a combined strategy. All other STS variables for the arthritic subjects were consistent with those reported in the literature. Similarly, Su, Lai, and Hong (1998) found that older adult subjects with osteoarthritis had longer total movement times, a greater forward displacement of the center of gravity, and a lower peak knee moment than the non-arthritic older adult subjects in their study, likewise suggesting that arthritic older adults employ a combined strategy in performing the STS movement.

Several studies have investigated the effects of hemiparesis (usually as a result of stroke) on the STS movement. Yoshida, et al. (1983) found that hemiparetic subjects required a greater overall movement time to execute the STS task. Likewise, Hesse, Schauer, Malezic, Jahnke, and Mauritz (1994) found that hemiparetic subjects took significantly longer to execute the STS movement than healthy subjects. In addition, they found that for the hemiparetic subjects the center of gravity was close to the center of pressure at seat-off, whereas for the healthy subjects the center of gravity was located behind the center of pressure at seat-off. These results would suggest that the hemiparetic subjects used a stabilization strategy while heathy subjects used a momentum transfer strategy (Hughes, et al., 1994). The longer movement times seen in hemiparetic subjects has also been confirmed by other studies (Cheng, Liaw, Wong, Tang, Lee, & Lin, 1998; Engardt & Olsson, 1992).

*The Sit-to-Walk Movement*

As noted in the Introduction, although studies generally have the sit-to-stand task end with quiet standing, in reality more often than not gait is initiated during the last phase of the STS movement (hence the reason in the present study for naming this last phase the "transition phase"). Magnan, McFadyen, and St-Vincent (1996) investigated the effects of modifying the sit-to-stand task with the addition of gait initiation, which they dubbed the "sit-to-walk (STW) task." The key results from this study were as follows: First, the temporal characteristics (i.e., time to peak horizontal and vertical momentum, time at seat-off, and time to maximum height of the center of gravity) of the STW movement were similar to the STS movement. All of the events tended to occur earlier in the STW movement, but the differences were all non-significant. Second, while the mean maximal excursion of the center of gravity in the vertical direction was similar in the STW compared to the STS movement, the mean maximal excursion of the center of gravity in the horizontal direction was significantly greater for the STW *versus* the *STS* movement. Third, the horizontal and vertical components of the peak momentum of the center of gravity both were significantly greater in the STW condition versus the STS. In addition, while in the STS movement the horizontal momentum decreases slowly to zero after reaching its peak, in the STW movement the horizontal momentum initially decreases after reaching its peak, but then began to increase again. Fourth, the position of the center of gravity relative to the center of pressure at seat-off was similar for both the STW and STS movements. Lastly, the ground reaction force patterns at the feet were similar until seat-off for both the STW and STS movements. At the time of the peak vertical ground reaction force, which occurred shortly after seat-off, the STW condition showed an increased loading of the stance leg compared to the swing leg, whereas there was little difference between legs in the STS condition. Furthermore, whereas the STS movement showed the typical anterior-posterior force pattern of a propulsive force followed by a braking force, in the STW movement the braking force rapidly switched to a second propulsive force as walking was initiated.

### *The Sit-to-Stand Movement in Children*

As noted in the Introduction, only five previous studies (Brugnolotti, 1992; Cahill, et al., 1999; Francis, 1987; McMillan, 1998; and Scholz & Brandt, 1997) have investigated the STS movement in children. Of these, four were concerned with developmental aspects of the STS movement (Brugnolotti, Francis, Macmillan, and Scholz & Brandt), and only one (Cahill, et al.) directly investigated kinematic and kinetic variables, albeit less extensively than in the present study. The subsequent discussion will look first at the developmental aspects of the STS movement, including the development of the ability to stand directly from a supine position on the floor (while the latter information is not directly relevant to the present study, it does help to provide a picture of the development of another type of standing movement in children), and then will proceed to look at what is presently known about the mechanics of the STS movement in children. First, however, a brief discussion of developmental sequences will be presented, in order to provide a framework for subsequent discussion.

### *Developmental Sequences*

Two different methods have been proposed for applying developmental phases or stages to skill development. In the first method, known as the "whole body approach" or the "composite approach" (Seefeldt & Haubenstricker, 1982), each stage of development involves characteristic body positions and actions for various segments of the body, such as the arms and legs. When assessing which stage of development a child is in for a given skill, the action of the whole body—the arms, legs, and trunk, for example—is observed and the child assigned to a stage based on the characteristics of the total body action.

The "component approach" (Roberton, 1977, 1978a, 1978b), on the other hand, treats each body component (arms, legs, trunk, etc.) separately. Thus when assessing which stage of development a child is in for a skill, first the arm action would be observed and the child assigned to a given stage for the arm component of the skill, then the leg action would be observed and the child assigned to a given stage for the leg component of the skill, etc.. In other words, whereas the composite approach may place Child A in Stage 1 and Child B in Stage 2 based on overall body action, the component approach may have Child A in Stage 1 for each body component (arm, leg, and trunk), but Child B in Stage 2 for the leg component, Stage 1 for the arm component, and Stage 2 for the trunk component.

The composite approach has the advantage of being less complex, and also takes a more integrated (in terms of body actions) approach to the development of motor skills. Although slightly more complex, the component approach has the advantage of allowing for differences in the rate of development for different body components, thus providing for an accounting of more subtle changes in the development of motor skills.

Regardless of which method is used, the same basic principles apply to developmental sequences (Seefeldt & Haubenstricker, 1982). The major principle of developmental sequences is that individuals pass through the various stages of a skill in a particular order. In other words, an individual would not progress from Stage 1 to Stage 4, then to Stage 2, and finally Stage 3. It is possible, however, for an individual to skip a stage or to temporarily regress to the previous stage. In addition, developmental sequences are age-related, not age-dependent. Thus, while mean ages for the attainment of a particular stage might be given in the literature, it must be understood that different individuals, all of whom are developing normally, may progress through the developmental sequence at different rates.

*Development of Rising from a Supine Position*

Typically infants are able to walk independently before they are able to independently rise from a supine to an erect position (Bayley, 1969; McGraw, 1943). The mean ages at which children are able to achieve these two milestones of development are

11.7 months and 12.6 months, respectively (Bayley, 1969). Furthermore, the ability to roll from a supine to a prone position, and the ability to assume an independent sitting position (milestones that occur before the ability to walk independently), are prerequisites for rising from a supine position (McGraw, 1943).

McGraw (1943) identified two distinct phases in the development of independent rising from a supine position. The first phase involves the infant first rolling from a supine to a prone position, and then pushing him or herself up with the hands. As the chest is raised off of the floor, first one foot and then the other are placed in contact with the floor so that the infant assumes a quadrupedal position. From this position, the hands are removed from the floor and the trunk extended. As noted above, Bayley (1969) found the mean age at which this phase occurs is 12.6 months.

In the second distinct phase described by McGraw (1943), the child pushes against the floor with one or both arms in order to rise to a seated position. As the child approaches the seated position, the lower extremities are flexed in order to place the feet on the floor, and then as the child pushes with the supporting hand or hands, the knees are extended and the body is raised to an erect posture. The mean age at which this phase occurs is between 30 and 46 months (Bayley, 1969; McGraw, 1943).

There is, of course, a relatively smooth transition between the two phases just described. For instance, by about 22 months of age the child does not roll completely to a prone position, but simply rolls to one side and then pushes the body up as described for the first phase (Bayley, 1969; Schaltenbrand, 1928). Alternately, the child may rise to a seated position as described for the second phase, but then flex the trunk and hips so that the hands can contact the floor. The child then rises to an erect position by assuming the quadrupedal form described in the first phase (McGraw, 1943).

The results of those studies that have investigated the ability of infants and children to rise from a supine position suggest that a relatively mature form of rising is achieved by approximately 4 years of age (Bayley, 1969; McGraw, 1943; Schaltenbrand, 1928). VanSant (1988), however, was interested in what differences, if any, exist in the movement patterns of children aged 4 to 7 years in rising from a supine position to erect stance. The results of VanSant's study indicated that while variation certainly existed among the 120 subjects, the predominant movement pattern at each age was similar to the mature pattern described by McGraw. Thus it appears that while individual variations in rising from a supine position may exist after 4 years of age, and immature patterns may still persist, by this age a relatively mature form of rising from a supine position has been achieved.

*Development of the Sit-to-Stand Movement in Children*

As has been previously noted, only four studies (Brugnolotti, 1992; Francis, 1987; McMillan, 1998; and Scholz & Brandt, 1997) have investigated the development of the STS movement in children. The study by Francis was a cross-sectional study of children ages 4 to 10 years, whereas Brugnolotti, McMillan, and Scholz and Brandt followed children (N= 4, N=5, and N=5, respectively) longitudinally from approximately 13 to 24 months of age.

In her study, Francis chose to use the component approach (Roberton, 1977) to describe the development of the STS movement. Francis defined descriptive categories for each component, and then placed each subject into a particular category. It should be noted that in her study, Francis did not restrict the movement of her subjects in any way; they were free to place their legs in any initial position and to use their arms in any way they wished. However, the chairs did not have armrests, although they did have a straight back rest. (Interestingly, Francis made no assessment as to whether the subjects used the back rest in performing the STS movement.)

In looking at the arm component, the results indicated that 4- and 5-year-old children most frequently pushed on the seat of the chair with the hands, whereas 6- and 10- year-old children tended to push on their legs with their hands, and young adults either pushed against their legs or swung their arms forward. As far as the trunk component was concerned, the 4- and 5- year-old children and the young adults fully flexed their trunk during the movement and trunk extension did not begin until after lift-off. Recall that this is the normative pattern for the momentum transfer strategy (Hughes, 1994) most often employed by young, healthy adults in performing the STS. The 6- and 10-year-old children, however, more frequently began extending the hip and trunk prior to lift-off. In terms of the leg component, Francis focused on the initial position and initial movement of the feet and legs. The results showed that in each age group, the most common pattern was picking up the feet slightly and repositioning them. Unfortunately, Francis did not report where the feet were repositioned. It would be assumed, based on the literature, that the feet would be repositioned such that the knee joint is at greater than 90° of flexion (Shepherd and Gentile, 1994). It is interesting, however, that, in an unrestricted situation, movement of the feet during the transition from sitting to standing may be a natural occurrence.

Brugnolotti (1992) measured the so-called "V/H ratio", i.e., the ratio of the vertical velocity of the seventh cervical vertebra to the horizontal velocity of the seventh cervical vertebra. This ratio was first described by Jones, et al. (1963), who used it to distinguish between able-bodied subjects and those with neurological impairments. Brugnolotti found that the V/H ratio decreased for all four subjects during development, although the factor that caused the decrease (i.e., decreased vertical velocity, increased horizontal velocity, or a combination) was varied.

McMillan (1998) and Scholz and Brandt (1997) followed the same five subjects longitudinally but focused on different aspects of the sit-to-stand movement. Scholz and Brandt measured the intertrial variability of the movement trajectories of the center of gravity of the body and the head, and related this to the body segment motion variability. The authors concluded that the STS movement is organized mainly around controlling the body's center of gravity trajectory and, after lift-off from the seat, the horizontal trajectory of the head, as opposed to controlling individual segmental movements. Furthermore, these results were evident even in the youngest infants (about 13 months of age) and remained consistent during development.

McMillan (1998) investigated several other aspects related to the development of movement coordination in the sit-to-stand movement. The aspect studied that is most relevant to the present study was the predominant movement pattern used by the children in performing the STS movement. McMillan identified two distinct patterns based primarily on the amount and speed of trunk flexion (both of these were assessed qualitatively) used in the movement. One pattern, which McMillan called the "forward-up" pattern, involved little trunk flexion with the body being repositioned at the beginning of the movement to bring the center of gravity closer to the base of support at seat-off. A second pattern, which McMillan called the "diagonal-up" pattern, involved significant trunk flexion. McMillan also observed that some subjects used a combination of the forward-up and diagonal-up patterns. Based on McMillan's descriptions, it would seem that the forward-up pattern is similar in at least some aspects to the stabilization strategy described by Hughes, et al. (1994), and the diagonal-up pattern is similar in at least some aspects to the momentum transfer strategy described by Hughes, et al.. McMillan found that there was a trend toward increasing use of the diagonal-up pattern with increasing age, with a corresponding decrease in the use of the forward-up pattern. This is consistent with Hughes, et al. who suggested that the stabilization strategy (similar to McMillan's forward-up pattern) would be used by those with less balance and postural control (i.e., at the younger ages), while the momentum transfer strategy (equal to McMillan's diagonal-up pattern) would be used by those with greater balance and control (i.e., at the older ages); the same is argued by McMillan.

*The Mechanics of the Sit-to-Stand Movement in Children*

To date (not including the present study) the study by Cahill, et al. (1999) represents the only study of any kind of the mechanics of the STS movement in children. The authors looked at the performance of the STS among three different age groups: 12 to 18 months, 4 to 5 years, and 9 to 10 years. The kinematic and kinetic variables they examined were: total movement time, amount of hip flexion and peak hip flexion angular velocity, and magnitude and time of occurrence of the peak vertical ground reaction force at the feet. Cahill, et al. found that movement time increased significantly with increasing age, with means of 1.0, 1.2, and 1.4 seconds for the three age groups, respectively. These values are generally faster than those reported in the literature for adults (see Table 10 in the Discussion section for a comparison). Cahill, et al. offer no explanation as to why movement time increased with increasing age, or why the movement times were faster than those reported for adult subjects. Similarly, the amount of hip flexion and the peak hip flexion velocity increased significantly with increasing age. The authors argue that as children develop greater postural and motor control they are able to flex the hips more and at a greater velocity. This suggests that younger children, who have less postural control and balance, employ more of a stabilization strategy (Hughes, et al., 1994), which is characterized by smaller hip flexion, and older children, who have greater postural control and balance, employ more of a momentum transfer strategy (Hughes, et al., 1994), which is characterized by greater hip flexion. These results are also consistent with the developmental changes in movement patterns observed above by McMillan (1998) and discussed above. Cahill, et al. found that the younger children took longer to reach the peak vertical ground reaction force at the feet than did the older children (probably due to lower postural control), whose force patterns were very similar to adults. The magnitude of the peak force (normalized to body weight), however, was not different among the age groups and was similar to that reported in the literature for adult subjects. Cahill, et al. conclude that the STS movement pattern is relatively well-established by 13 months of age, and is similar to that of older children and adults, the main differences being a faster movement time in the younger children, increasing hip flexion and hip flexion velocity with increasing age, and longer time to peak force in the younger children. These latter two results were attributed to less postural control and balance in the younger children.

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# METHODS

## *Subjects*

Subjects were recruited personally by the author from the children of Michigan State University faculty, staff, and graduate students; and from the greater Lansing area. After a parent expressed willingness to have his or her child participate in the study, a letter was sent to the parent further explaining the purpose of the study and the details of the data collection procedure. When the parent(s) and child(ren) arrived at the laboratory (one of) the parent(s) was asked to read and then sign an informed consent form (see Appendix A). Prior to data collection, approval for this research project was obtained from the University Committee on Research Involving Human Subjects.

The subjects consisted of 12 children, 4 males and 8 females, in one of three age categories: 12-18 months, hereafter referred to as Group 1 (N=5; mean age 14.7±1.7 months); 24-36 months, hereafter referred to as Group 2 (N=3; mean age 26.5±2.3 months); and 48-60 months, hereafter referred to as Group 3 (N=4; mean age 51.5±5.2 months); one additional subject had to be eliminated from the study due to an unwillingness to cooperate. The subjects were all healthy individuals with no known injury, orthopedic problem, and/or disability that limited normal physical development or their performance of the STS movement. The characteristics of each subject are shown in Table 4.

**Table 4.** Subjects' personal characteristics.

| Subject ID | Sex | Age (months) | Height (cm) | Mass (kg) |
|---|---|---|---|---|
| 1 | F | 48.0 | 104.0 | 15.7 |
| 2 | F | 26.0 | 84.0 | 9.6 |
| 3 | M | 29.0 | 84.5 | 8.7 |
| 4 | F | 51.0 | 102.6 | 17.0 |
| 5 | M | 17.0 | 74.5 | 10.9 |
| 6 | M | 59.0 | 105.8 | 14.6 |
| 7 | F | 24.5 | 84.7 | 10.3 |
| 8 | F | 15.0 | 77.5 | 10.1 |
| 9 | F | 48.0 | 98.6 | 15.9 |
| 10 | F | 13.0 | 74.8 | 9.8 |
| 11 | M | 13.0 | 75.8 | 10.3 |
| 12 | F | 15.5 | 75.1 | 9.6 |

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### *Stool*

A custom-built stool was used, which can be adjusted from a seat height (including the height of a mounted force platform) of 30 cm to a height of 50 cm in 2 cm increments (see Figure 3). The stool has no back rest and the surface of the seat is flat and designed for the mounting of a force platform. The height of the stool was adjusted to 100% of the individual's projected calf-length (see section on "Anthropometric Measures") thus positioning the subject so that the thighs were parallel to the ground.

### *Videographic System*

Although one study of adults found that the STS movement may not be entirely symmetrical (Lundin, Grabiner, & Jahnigen, 1995), the differences between the right and left side were small, and therefore although "statistically significant, the biomechanical significance of differences of this magnitude may be small (p. 112)." In addition, qualitative observation of children performing the STS has suggested that young children perform the movement in a fairly consistent, symmetrical manner. In the present study, therefore, it was assumed that the STS movement was bilaterally symmetrical, with the movement taking place primarily in the sagittal plane. Therefore kinematic data collection was limited to two dimensions. A single Panasonic S-VHS video camera (model AG-455) was placed with the optical axis of its lens perpendicular to the sagittal plane of the subject, and had a speed of 60 fields per second (60 Hz), and a shutter speed of 1/1000 of a second. Data contained in the literature has shown that this frame rate and shutter speed are more than adequate for the STS movement, which is generally completed in between

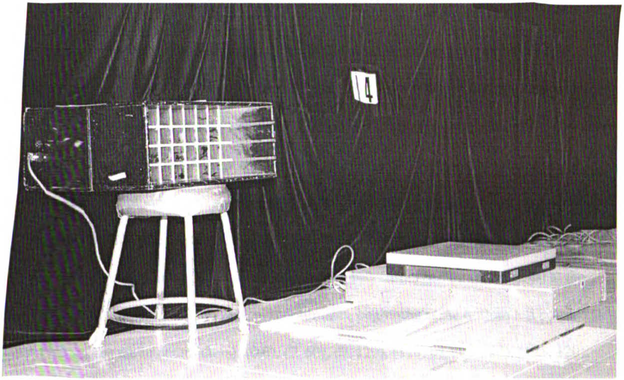


**Figure 3a.** Photograph of the experimental set up, showing the adjustable stool with mounted force platform, special flooring over the force platform at the feet, and timing lights.

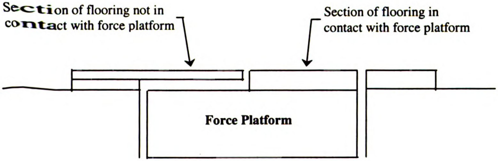


**Figure 3b.** Cross-sectional view of the construction of the special plywood flooring covering the force platform used to isolate only a single foot.

1.0 and 2.0 seconds (Shepherd & Gentile, 1994). The camera lens was zoomed in so that the field of view (FOV) was as small as possible (thereby making the subject to appear as large as possible) while still capturing all of the movement and any other relevant background information (such as timing lights). Prior to the beginning of a data collection session, a calibration structure consisting of a series of strings, each containing a number of reflective styrofoam balls at even increments along its length, suspended from an overhead aluminum frame and weighted with plumb bobs was placed in the center of the camera's FOV (see Figure 4). For the present study the calibration structure consisted of six known data points (two balls plus the plumb bob suspended on two strings) at the following x (horizontal), y (vertical) coordinates, beginning at the bottom left corner (all coordinates are in centimeters): (0,0), (0, 60), (0, 120), (123, 0), (123, 60), (123, 120).

*Force Platforms*

Kinetic data were collected simultaneously with the videographic data using two force platforms (AMTI model OR6-5-2000): one placed beneath the subject's feet (note that the legs of the stool were not in contact with the force platform) and one placed on the surface of the seat. In order to ensure that only the right or left foot was in contact with the force plate beneath the feet during the movement special flooring was used. This flooring consisted of a piece of plywood that extended over the force platform and was not in contact with it, and a second piece that was placed on the force platform and adhered to it using sheet magnets; the overall height of the plywood pieces was the same (see Figure 3). The result was that the subject placed one foot on the piece of plywood in direct contact with the force platform (i.e., the foot on the side facing the video camera)

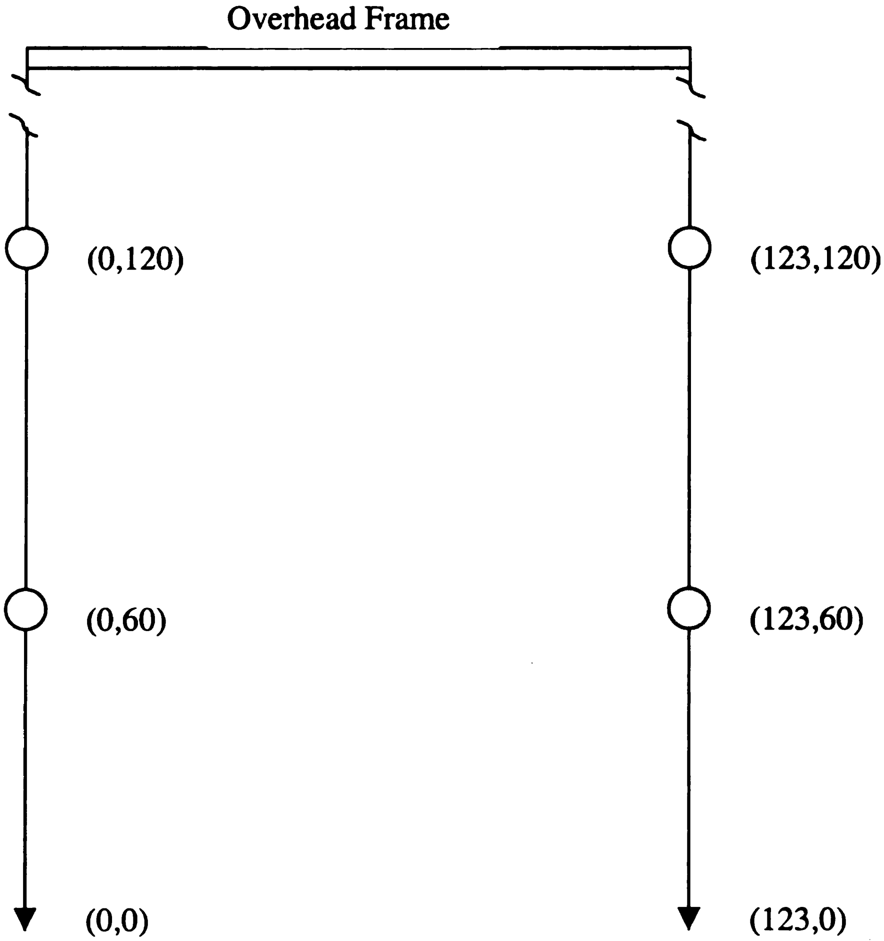


**Figure 4.** Diagram of the calibration structure, showing strings weighted with plumb bobs and suspending reflective styrofoam balls. The coordinates of the balls and plumb bobs are also shown.

and one foot on the piece not in contact with the force platform (i.e., the foot on the side not facing the camera). It was found during pilot testing that the use of this special flooring did not significantly attenuate or in any other way alter the kinetic data. The sampling frequency for the force platform was 1000 Hz, although when the kinematic and kinetic data were analyzed together, this rate was reduced to 60 Hz to match that of the video data (this was accomplished by first interpolating data points to reach 1200 points per second, and then taking one out of every 20 data points to arrive at 60 Hz). Even though the STS movement takes only about 1.0 to 2.0 seconds to complete, the force data were collected for a five-second period to ensure that the entire event was captured. The force platforms recorded three orthogonal forces (anterior-posterior, medial-lateral, and vertical) and three orthogonal moments about the x, y, and z axes. In addition, the center of pressure (i.e., the anterior-posterior point of application of the net ground reaction force) location relative to the center of the force platform at any given time was calculated by dividing the moment about the medio-lateral axis by the vertical force (Kralj, et al., 1990). This position relative to the center of the force platform was then related to the x, y coordinate system of the videographic system.

*Synchronization of Video and Force Data*

The video record and the force platform data were synchronized during analysis by matching the observed moment of seat-off on the video record with the moment at which the vertical force of the force platform on the seat dropped to zero. This synchronization was confirmed through the use of timing lights which were visible in the

camera's field of view and changed position every 1/1000 of a second, and which provided an analog signal every second that was superimposed on the force record.

### *Data Acquisition System*

The Ariel Performance Analysis System (APAS) was used to acquire analog data, to capture and digitize video data, and to filter and smooth the kinematic data. The APAS consists of: a computer and software to perform the above mentioned functions, a Panasonic Video Cassette Player (model AG-7150), and a 16-channel A/D board, of which 14 channels were used in the present study (three for the orthogonal forces from the first force platform, three for the orthogonal moments from the first force platform, three for the orthogonal forces from the second force platform, three for the orthogonal moments from the second force platform, one for the timing light signal, and one for an external trigger system). More detail is provided on the use of the APAS in the discussion on Procedures and the discussion on Data Analyses.

## *Biomechanical Model*

The biomechanical model that was used for all analyses consisted of four linked rigid bodies: One each to represent the foot, shank, leg (thigh), and the torso; because use of the arms was restricted, the three segments of the upper extremity (arm, forearm, and hand) were not included in the model. This model and associated angles are shown in Figure 2. All segments were assumed to move only in the sagittal plane. The points on the body that were digitized to define each segment were as follows: foot, base of the fifth metatarsal and the lateral malleolus; shank, lateral malleolus to the center of the knee joint (i.e., between the lateral condyles of the femur and tibia); thigh, center of the knee joint to the greater trochanter; torso, greater trochanter to the acromion process. Note here that the torso consists of the pelvis and the trunk but is treated as one segment; i.e., movement was limited to the hip joint as opposed to considering movement at both the hip and lumbosacral joints.

A difficulty one has when performing biomechanical analyses on children, especially those analyses that require information on segmental centers of gravity, segmental masses, and/or radii of gyration, is the relative lack of data of this kind on children. It is assumed here, of course, that standard anthropometric data on adults, such as that derived from Dempster (1955) or Clauser (Clauser, McConville, & Young, 1969), should not be extrapolated to children. For these reasons, Jensen (1986) set out to determine body segment mass, center of gravity, and radius of gyration proportions for children. Jensen's subjects consisted of males between the ages of four and fifteen. The result of his study was a series of regression equations for the above-mentioned variables based on age. While Jensen's study provides much-needed anthropometric information on children, there is still a lack of data on children younger than 4 years of age. In fact, the lowest age limit of Jensen's study represents the highest age limit of the present study. Nevertheless, despite the inherent dangers of extrapolating data outside of the population for which those data have been validated, the decision was made to use Jensen's regression equations to calculate the segment mass, center of gravity, and radius of gyration proportions for children in the present study because these equations provided a means for determining, based on age, more accurate segment mass, center of gravity, and radius of gyration proportions than would have been obtained by using adult data.

*Anthropometric Measures*

The following direct anthropometric measurements were used in the present study:

(1) Weight: At the beginning of data collection each subject stood on one of the force platforms and his or her weight to the nearest 0.1 N was measured.

(2) Height: A moveable anthropometer was used to measure height (stature) in centimeters to the nearest millimeter. The procedure used was that prescribed by Gordon, Chumlea, and Roche (1988).

(3) Projected Calf Length: Projected calf length is the vertical distance from the proximal surface of the tibia to the sole of the foot. A moveable anthropometer was used to measure projected calf length in centimeters to the nearest millimeter. This value was then used to adjust the stool to the appropriate height. The procedure used was that prescribed by Martin, Carter, Hendy, and Malina (1988).

All anthropometric measurements were taken on the right side of the body, as this is the standard in the United States (Lohman, Roche, & Martorell, 1988). Note that segment lengths were not measured anthropometrically, but instead were determined after the video images were digitized by measuring the distance between corresponding joint centers.

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## *Procedures*

### *Subject Preparation*

Upon arriving at the testing location, parents were reminded of the purpose of the study and the procedures that would be followed, and were asked to sign the statement of informed consent. Once this has been done, the aforementioned anthropometric measures were taken, and the subject's projected calf length was used to adjust the height of the stool to 100% of projected calf length. All subjects performed the STS barefoot, with the younger subjects wearing only a diaper and the older subjects wearing a swimsuit. The choice of a swimsuit versus a diaper depended in part on age, but also on the comfort of the child and his or her parent.

### *Data Collection*

Each subject was seated on the force platform on the adjustable stool by his or her parent and positioned in such a way that the edge of the seat contacted the popliteal region. The position of the feet on the force platform was not restricted, although it was assured that the height of the stool was such that the subject could easily contact the force platform with the entire plantar surface of the foot, and that the correct foot was placed on the force platform with the opposite foot off the platform (i.e., the section of flooring not in contact with the force platform). The subject's arms were restricted during the movement by having the subject hold a small stuffed animal in his or her hands. Once the requisite position had been achieved, the parent gave the child encouragement to stand up, at which point an external electronic excitation device was used to trigger the force platforms. The video camera was turned on just prior to the first trial and recorded continuously until the end of the data collection period. No attempt was made to control the speed of ascent, but rather the goal was to have the subject perform the STS in a natural manner and at a natural speed (whatever speed that might happen to be). In addition, no attempt was made to restrict the subject's movement after the STS was completed, although the older subjects were asked to remain standing for a brief period. More often than not, the younger children transitioned directly from the STS into a walk toward their parents (what might be termed a "sit-to-walk pattern"; Magnan, et al., 1996). The subject continued to perform trials of the STS movement until at least ten acceptable trials per side of the body were achieved (in some cases as many as twenty trials per side of the body were performed). Once this was accomplished, the subject was given a brief break and then data collection resumed on the opposite side of the body. The side of the body on which data were collected first (right or left) was randomized. The criteria used to determine if a trial was acceptable were:

(1) A complete video record of the trial was obtained. This criterion was virtually guaranteed by continuous running of the video camera.

(2) A complete force record of the trial was obtained. Lack of a complete force record, due to error in triggering the force platform, was the most common cause of making a trial unacceptable.

(3) The subject did not use his or her hands to push off of the stool or in any other way to assist in performing the STS.

(4) The subjected performed the STS in what appeared to be a natural manner, without a loss of balance, and neither excessively slowly or excessively fast.

No specific times or speeds were used for this latter criterion; this was a subjective, qualitative measure.

## *Data Analysis*

### *Digitization and Video Processing*

At the completion of data collection the video and force records were reviewed, and the first five trials from each side of the body that were confirmed to have met the required performance criteria were selected for analysis. Using the APAS the video record of each trial was first captured, then the beginning and end of the movement were identified, and then all of the fields of video representing the trial were saved, plus ten additional fields before the start of the movement and ten additional fields after the end of the movement. Because each subject self-selected the speed at which the STS was performed, and the movement time therefore varied, the number of fields of video ultimately digitized varied from trial to trial and subject to subject. Once the complete video record of the trial (plus the additional fields before and after) was saved, the five data points (base of the fifth metatarsal, lateral malleolus, center of the knee, greater trochanter, and acromion process) were digitized by hand for each field of video. The six points on the calibration structure were also digitized for each trial. Once the entire trial had been digitized, the raw coordinate data were filtered and smoothed using a cubic spline.

*Force Data*

The analog signals from each of the two force platforms passed through an analog-to-digital converter and the three orthogonal forces and three orthogonal moments from each were recorded. The 1000 points of data per second were then reduced to 60 points per second in order to match the frequency of the video data. As noted above, this was accomplished by first interpolating data points to reach 1200 points per second, and then taking one out of every 20 data points to arrive at 60 points per second. The force and video data were then synchronized using the method described above.

*Variables Obtained*

Using the APAS the following variables were obtained and used for subsequent analysis (two analyses are discussed in more detail below) and/or discussion:

(1) position (x, y) of the base of the fifth metatarsal, lateral malleolus, center of the knee joint, greater trochanter, and acromion process;

(2) linear acceleration (x, y) of the base of the fifth metatarsal, lateral malleolus, center of the knee joint, greater trochanter, and acromion process;

(3) angular acceleration of the foot, shank, and thigh segments;

(4) angular position of the ankle, knee, and hip joints;

(5) angular velocity of the ankle, knee, and hip joints;

(6) position (x, y) and velocity (x, y) of the whole-body center of gravity (based on Jensen's [1986] data);

(7) vertical and horizontal ground reaction forces at the feet and the moment about the medio-lateral axis at the feet; and

(8) vertical and horizontal ground reaction forces at the buttocks.

### *Movement and Phase Times*

As noted in the Introduction and the Review of Literature, the *STS* was divided into four phases: flexion-momentum (from initiation of the movement to seat-off), momentum-transfer (from seat-off to maximum ankle dorsiflexion), extension (from maximum ankle dorsiflexion to cessation of hip extension), and transition (from cessation of hip extension to normal postural sway or to the initiation of a subsequent movement); see also Figure 1. This last phase, because of its highly variable nature, was not included in the analyses and discussion. The total movement time for the STS was determined to be the time from the initiation of movement until the cessation of hip extension (i.e., the end of Phase 3). The movement time (in seconds) for each phase was determined using the defining events listed above; each phase time was also expressed as a percentage of total movement time in order to allow for comparison among trials of different lengths.

### *Joint Moments*

The moments about the medio-lateral axis of the hip and knee joints during extension were calculated using the process popularly known as "inverse dynamics," and which has been detailed by (among others) Winter (1990). In this process free-body diagrams of each segment are drawn, beginning with the foot. Based on the vertical and horizontal ground reaction forces located at the center of pressure (note that because hip and knee extension occur after seat-off, only the ground reaction forces at the feet need to be considered), the moment at the center of pressure about the medio-lateral axis, the foot

length, the center of gravity location of the foot, the mass of the foot, the linear acceleration at the center of gravity of the foot, the moment of inertia of the foot, and the angular acceleration of the foot. One can use the rules of mechanics to calculate the vertical and horizontal forces and the moment about the ankle joint. Once these values are known, one can then move to the adjoining segment above, namely the shank, and use a similar procedure to determine the forces and moments at the knee joint (although now things are simplified somewhat, as one only has to consider the forces and moment at the ankle, and the mass, moment of inertia, and linear and angular accelerations of the shank at its center of gravity). The same process is followed to calculate the forces and moments at the hip joint, once the knee joint forces and moments have been determined. In the present study a Qbasic (version 1.1) computer program was written to perform all of the calculations and iterations necessary to carry out the inverse dynamics procedure; this program can be found in Appendix B. For the purposes of comparison, the joint moments were normalized by dividing by body weight in newtons, multiplying by height in meters, and multiplying by 100 (Ikeda, et al., 1991).

*Variables Reported and Discussed*

After all calculations and analyses were complete, the following groups of variables were selected for discussion, and are reported and discussed in the Results and Discussion sections, respectively:

(1) Movement times: total movement time, phase times in seconds, and phase times as a percentage of movement time.

(2) Joint ranges of motion: range of motion (i.e., greatest angle achieved during the movement minus the smallest angle achieved) of the hip, knee, and ankle joints.

(3) Joint angular velocities: the angular velocities at the hip, knee, and ankle joints.

(4) Velocity of the center of gravity: the horizontal and vertical components of the velocity of the whole-body center of gravity. In the Discussion section the velocity of the center of gravity is also used to derive the momentum and kinetic energy of the center of gravity.

(5) Ground reaction forces: the vertical and horizontal ground reaction forces at the feet and at the buttocks.

(6) Joint moments: the peak extension moments at the hip and knee joints.

*Statistical Analyses*

Granting that the small number of subjects in the present study decreases the power of any statistical analysis (and thus increases the risk of a Type II error), statistical analyses were nonetheless used to determine if there were any statistically significant differences in the above-mentioned variables among the three age groups in the study. The statistical analyses were conducted using the Statistical Package for the Social Sciences (SPSS; version 10.0). In most cases multivariate analysis of variance (MANOVA) was used, as each of the variable categories listed above has two or more dependent variables (e.g., horizontal and vertical components of the velocity of the center of gravity; angular velocities of the hip, knee, and ankle joints). In all cases the significance level was set at $\alpha = .05$.

# RESULTS

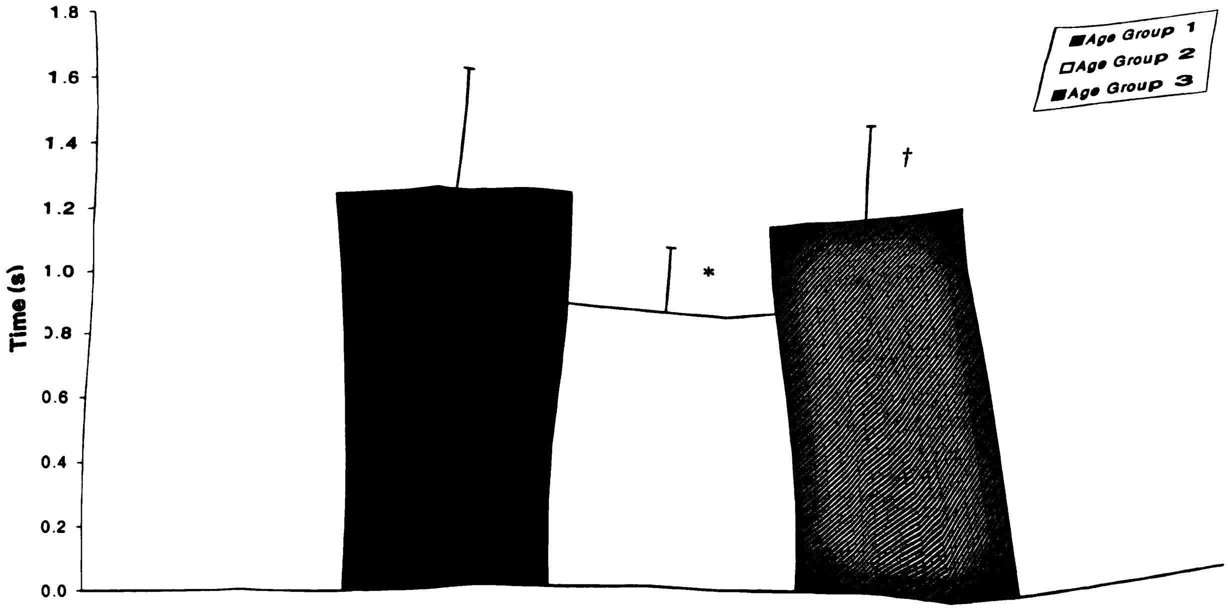
## *Right versus Left Side of the Body*

No significant differences were found within each subject when comparing the right and left side of the body for all of the variables considered. Therefore in the discussion that follows the data from the right- and left-side trials are treated collectively.

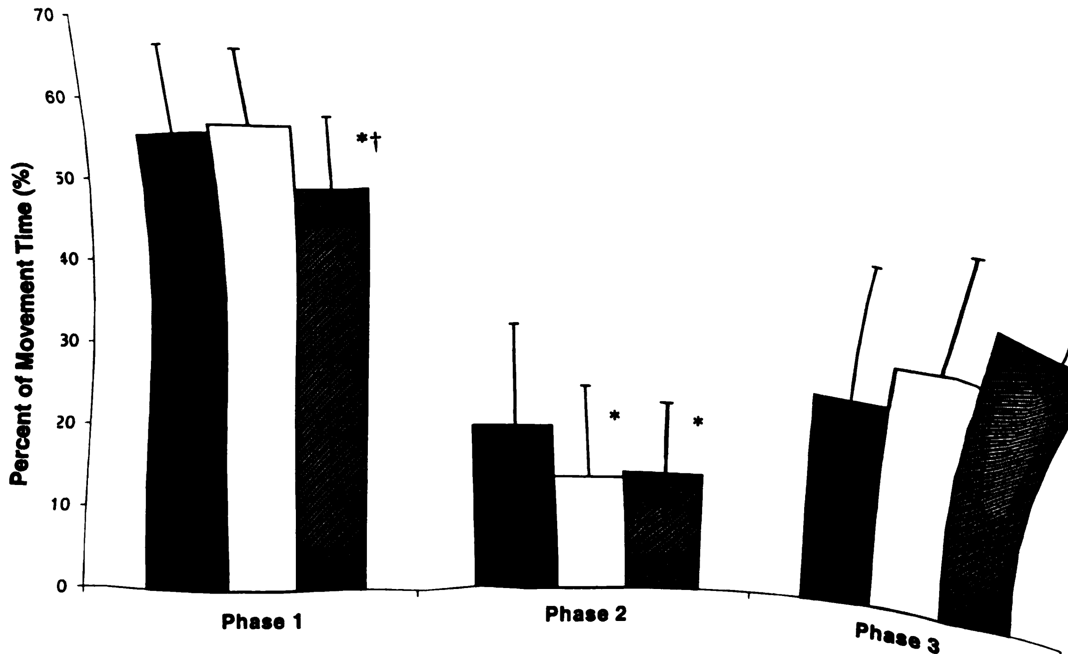
## *Movement and Phase Times*

The mean movement times for each age group are shown in Figure 5a (the mean movement times across ten trials for each subject can be found in Table C1 of Appendix C). The total mean movement time for Group 1 was the greatest at 1.2 ±0.4 s, followed closely by the Group 3 at 1.2 ±0.3 s; the mean movement time was not significantly different between these two groups. However, the mean movement time for the Group 2 was significantly shorter (0.9 ±0.2 s) than both of the other groups ($p < .01$). Of the three age groups, Group 1 had the greatest variability in movement time with a standard deviation equal to 31% of total movement time, followed by Group 3 at 27%, with Group 2 having the smallest variation at 24% of movement time.

The mean times for each age group for Phases 1, 2, and 3 of the movement, expressed as a percentage of total movement time, is shown in Figure 5b (the mean phase times and phase percents across the ten trials for each subject are also shown in Table C1). As a whole, the subjects spent just over half of the total movement time in Phase 1 (0.6 ±0.2 s or 53 ±10%). As for the remainder of the movement time,




(a)




(b)

* Significantly different from Group 1 (p<.05)
† Significantly different from Group 2 (p<.05)

**Figure 5.** Mean (+ 1 s.d.) movement time (a) and phase times as a percent of movement time (b) for the three age groups.

approximately one-third was spent in Phase 2 (0.2 ± 0.1 s or 16 ± 11%) and two-thirds in Phase 3 (0.4 ±0.3 s or 31 ±17%).

In comparing the three age groups, Group 1 spent significantly longer in Phase 1 ($p < .01$) and Phase 2 ($p < .05$) than did Group 3 (55 ±11% vs. 49 ±9% for Phase 1 and 20 ±12% vs. 14 ±9% for Phase 2), and significantly less time in Phase 3 ($p < .01$) than did Group 3 (25 ±17% vs. 38 ±15%). Groups 1 and 2 had similar phase times (as a percentage of total movement time) except for Phase 2, for which Group 1 spent a significantly longer time (20 ±12% vs. 13 ±11%; $p < .05$). Groups 2 and 3 significantly differed from each other only in Phase 1, for which Group 2 spent a significantly longer time (56 ±9% vs. 49 ±9%; $p < .01$).

### *Joint Range of Motion*

Although the groups differed in the total range of motion of each joint, the overall pattern of joint involvement was similar for each group. A representative graph of joint angular position versus time is presented in Figure 6. In addition, the mean total range of motion for the ankle, knee, and hip joints is shown in Figure 7 (the mean data for each subject can be found in Table C2 of Appendix C). The mean ranges of motion at the ankle, knee, and hip joints were the greatest for Group 3 (35 ±14°, 83 ±22°, and 113 ±16°, respectively), and were significantly different ($p < .01$) from both Groups 1 (29 ±12°, 61 ±16°, and 90 ±17°) and 2 (25 ±9°, 60 ±15°, and 86 ±14°), which were not significantly different from each other.

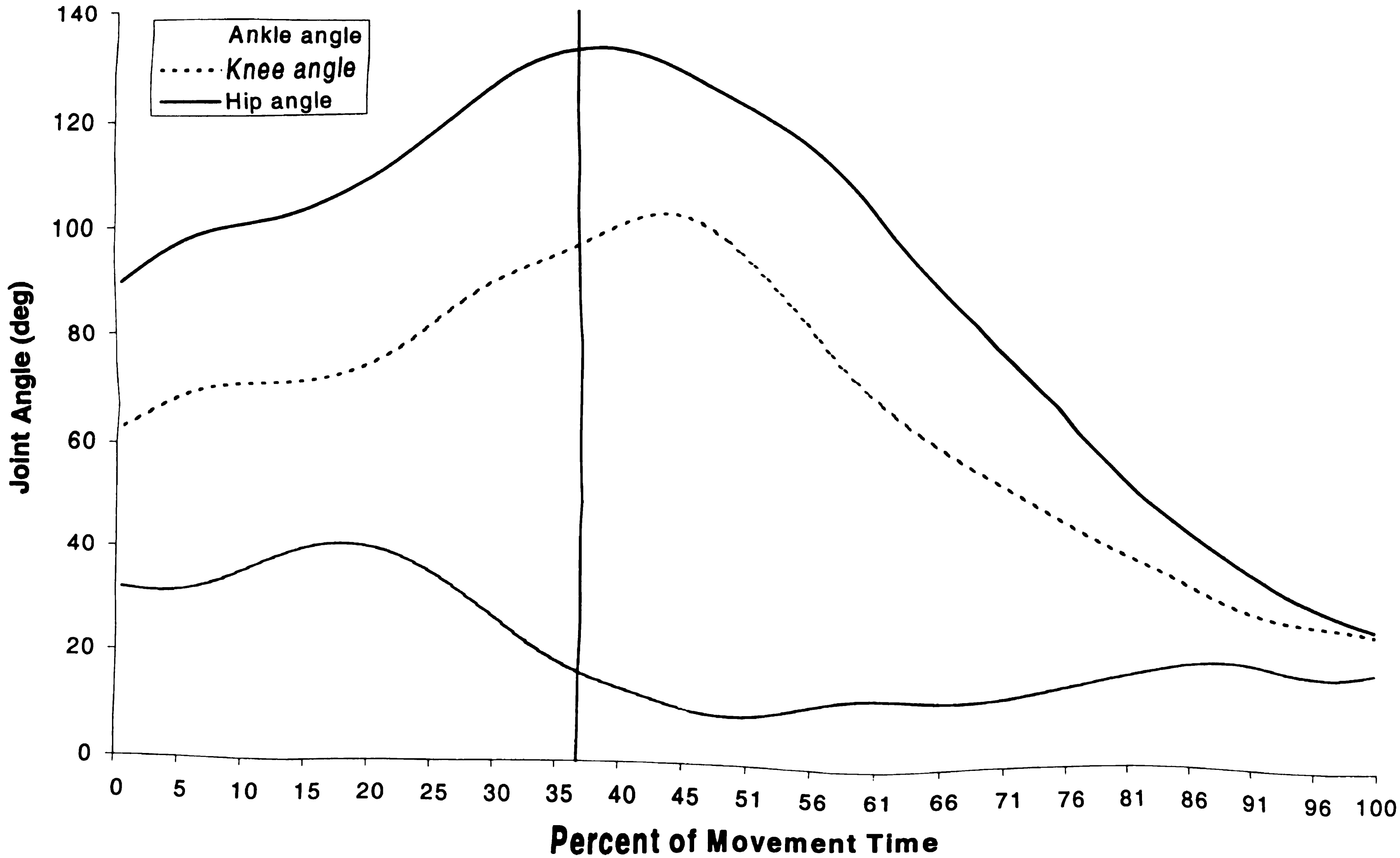
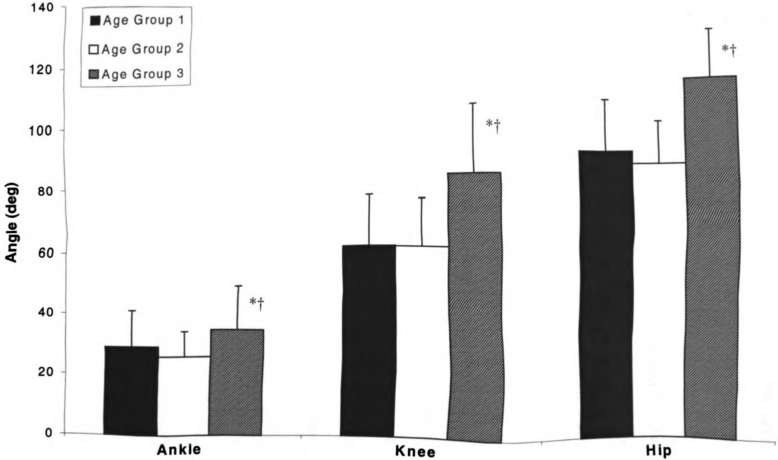



**Figure 6.** Representative time history of the ankle, knee, and hip joint angles.




* Significantly different from Group 1 (p<.05)
† Significantly different from Group 2 (p<.05)

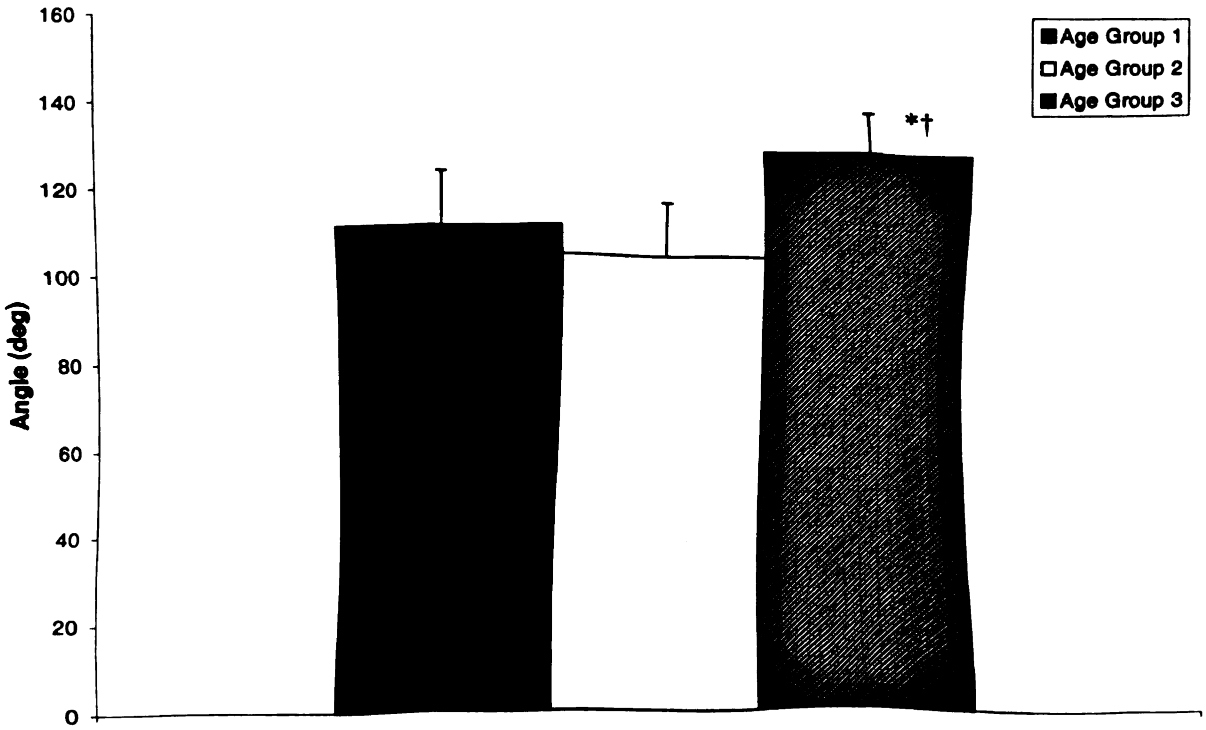
**Figure 7.** Mean (+ 1 s.d.) ranges of motion at the ankle, knee, and hip joints during the sit-to-stand movement for the three age groups.

The mean peak hip flexion angle and the mean time to peak hip flexion for each group (expressed as a percentage of total movement time) are shown in Figure 8; the mean data for each subject can also be found in Table C2. The mean peak hip flexion angle was also the greatest for Group 3 (127 ±9°), and was significantly greater ($p < .01$) than both Groups 1 (110 ±13°) and 2 (103 ±12°). The mean time to reach peak hip flexion was similar for all three groups (Group 1 = 38 ±12%, Group 2 = 43 ±8%, Group 3 = 40 ±6), although the time for Group 1 was just significantly less ($p < .05$) than that for Group 2. There were no significant differences between Groups 1 and 3 and between Groups 2 and 3.

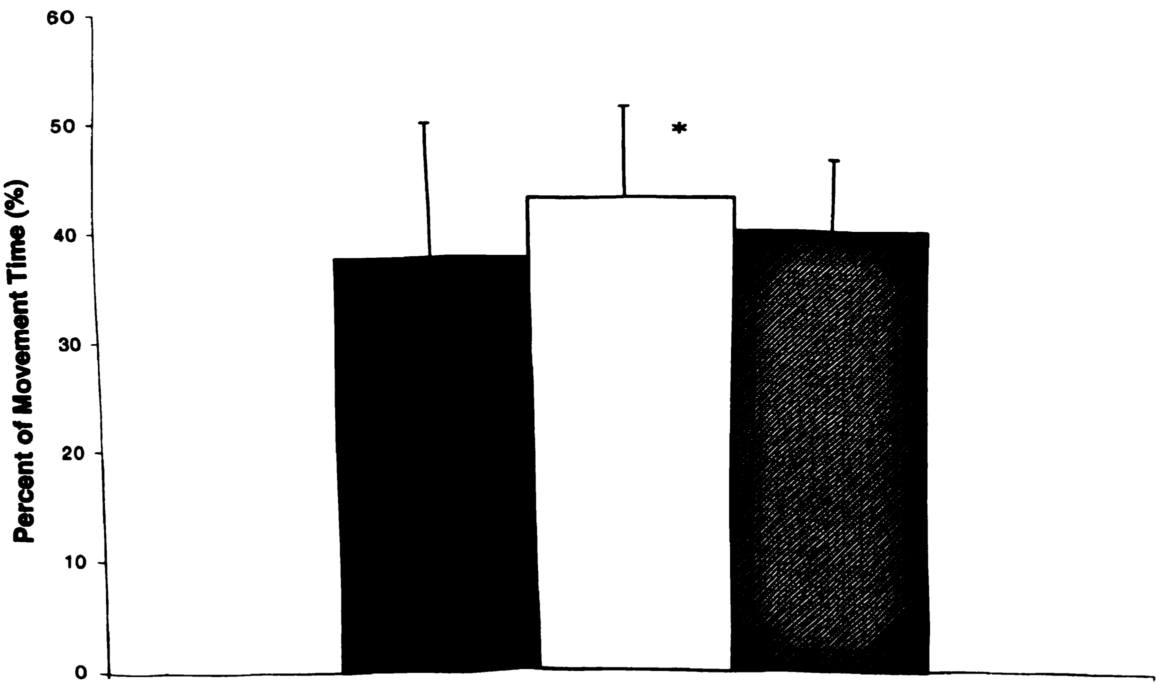
*Peak Joint Angular Velocities*

The mean peak angular velocities reached during hip flexion, hip extension, and knee extension are shown in Figure 9a, while the times required to reach peak hip flexion, hip extension, and knee extension angular velocities (expressed as a percentage of total movement time) are shown in Figure 9b; the mean data for all subjects can be found in Table C3 in Appendix C. The mean peak angular velocities during hip flexion, hip extension, and knee flexion for Group 1 (64 ±24°/s, 206 ±68°/s, and 143 ±62°/s, respectively) were significantly less ($p < .01$) than for Groups 2 (89 ±25°/s, 278 ±77°/s, and 208 ±73°/s) and 3 (105 ±46°/s, 264 ±82°/s, 206 ±73°/s), which were not significantly different from each other.

The mean time, as a percentage of total movement time, taken to reach peak hip flexion was significantly less ($p < .01$) for Group 1 (18 ±12%) than for Groups 2 (26 ±9%) and 3 (25 ±6%), which were not significantly different from each other. On



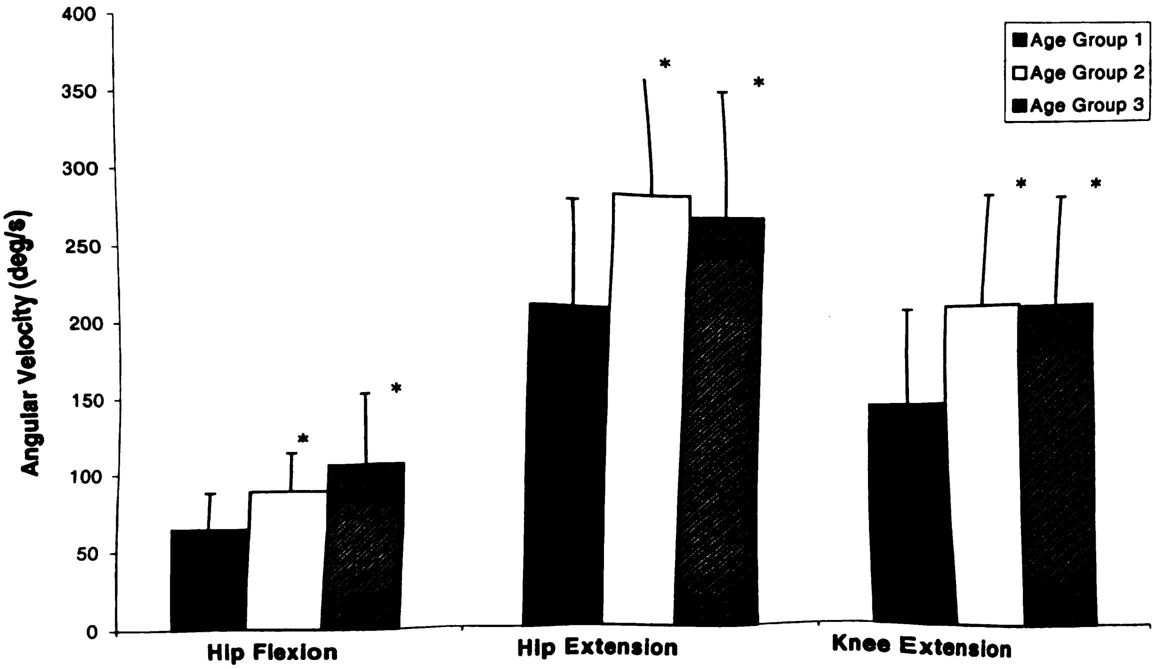

(a)



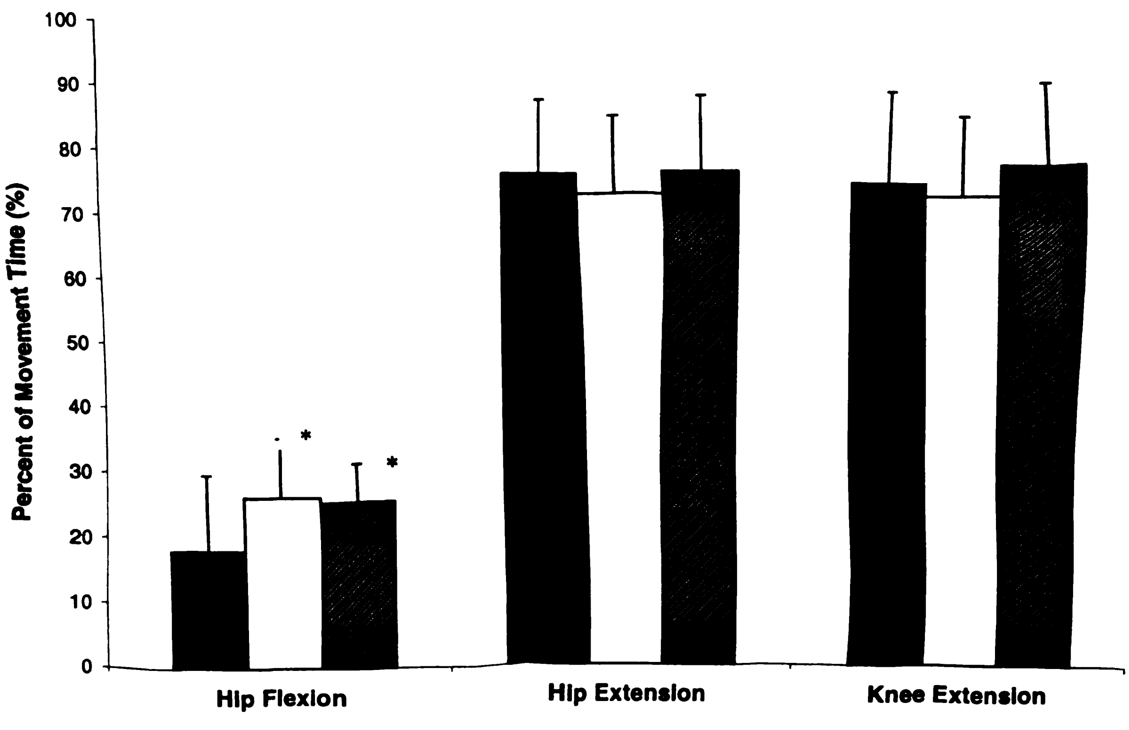

(b)

* Significantly different from Group 1 (p<.05)
† Significantly different from Group 2 (p<.05)

**Figure 8.** Mean (+ 1 s.d.) peak hip flexion angle (a) and the time to peak hip flexion as a percent of movement time (b) for the three age groups.




(a)




(b)

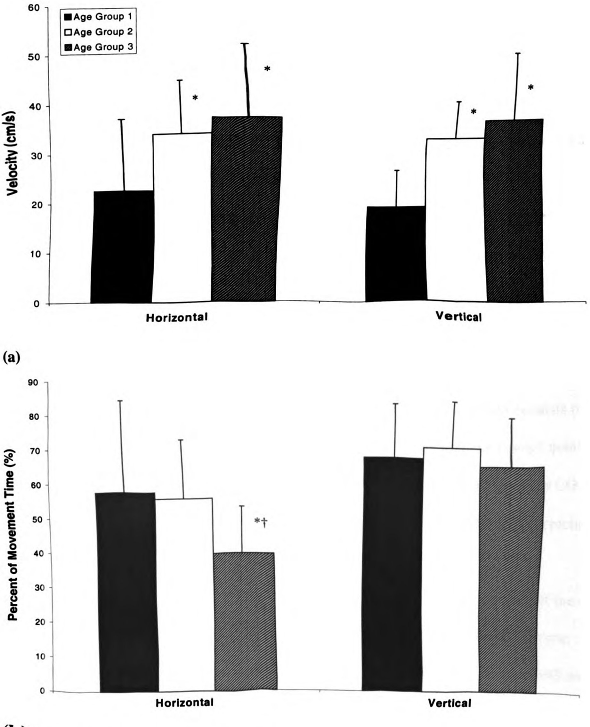
* Significantly different from Group 1 ($p<.05$)

**Figure 9.** Mean (+ 1 s.d.) peak hip flexion, hip extension, and knee extension velocity (a) and the time to peak velocity as a percent of movement time (b) for the three age groups.

the other hand, the mean time to peak hip extension velocity was not significantly different among the groups (Group 1 = 75 ±11%, Group 2 = 72 ±12%, Group 3 = 76 ±11%), nor was the mean time to peak knee extension velocity (Group 1 = 74 ±14%, Group 2 = 72 ±12%, Group 3 = 77 ±13%). As expected, peak hip flexion velocity occurred prior to seat off, with peak hip and knee extension velocities occurring close to each other and to the Phase 2-Phase 3 transition point.

*Velocity of the Whole-body Center of Gravity*

The mean peak horizontal (anterior-posterior) and vertical components of the velocity of the center of gravity (CG) of the whole body, as well as the mean time taken to reach peak horizontal and vertical velocity (expressed as a percentage of total movement time), for each group are shown in Figures 10a and b, respectively; the mean data for each subject can be found in Table C4 of Appendix C. The mean peak horizontal velocity of the CG was significantly less ($p < .01$) for Group 1 (22.5 ±14.5 cm/s) than for Groups 2 (33.9 ±10.7 cm/s) and 3 (37.0 ±15.2 cm/s), which were not significantly different from each other. The same was true for the mean peak vertical velocity of the CG: that for Group 1 (19.4 ±7.5 cm/s) was significantly less ($p < .01$) than for Groups 2 (33.4 ±7.6 cm/s) and 3 (37.0 ±13.9 cm/s), which were not significantly different from each other. Studies involving adult subjects have reported peak horizontal and vertical velocities as being of similar magnitude (Riley, et al., 1991). In the present study the mean peak horizontal and vertical velocities were similar in magnitude to each other, and were significantly correlated ($p < .01$), but the correlation was relatively low ($r = .42$). This result is not surprising, as there was a great deal of between-subject variability




* Significantly different from Group 1 (p<.05)
† Significantly different from Group 2 (p<.05)

**Figure 10.** Mean (+ 1 s.d.) peak horizontal and vertical velocity of the center of gravity (a) and the time to peak horizontal and vertical velocity of the center of gravity as a percent of movement time (b) for the three age groups.

(see Table C4).

The mean time taken to reach peak horizontal velocity of the CG was significantly greater ($p < .01$) for Groups 1 (58 ±27%) and 2 (56 ±17%) than for Group 3 (39 ±13%); there were no significant differences between Groups 1 and 2. There were no significant differences among the three groups in the mean time taken to reach peak vertical velocity (Group 1 = 68 ±15%, Group 2 = 71 ±13%, Group 3 = 65 ±14%).

Because linear momentum is dependent in part on linear velocity (and in part on body mass), the horizontal and vertical velocities of the CG provide a normalized measure of the horizontal and vertical linear momentum of the CG (i.e., momentum divided by mass). Although variation did exist from trial to trial and subject to subject, most trials exhibited the relationship between horizontal and vertical velocity (and thereby horizontal and vertical momentum) illustrated in Figure 11, which consists of a representative plot from each of the three age groups. In this pattern, the lowest point of the vertical velocity of the CG coincides with the peak horizontal velocity of the CG. Then as the horizontal velocity decreases the vertical velocity increases until it reaches its peak.

On average (with the exception of Subject 5) the peak vertical velocity of the CG occurred after the peak horizontal velocity had been reached. The difference in time between peak vertical velocity and peak horizontal velocity tended to increase with each age group: a difference of 10% of total movement time for Group 1, 15% for Group 2, and 26% for Group 3 (see Figure 11). This time difference was significantly greater ($p < .01$) for Group 3 versus Groups 1 and 2, which were not significantly different from each other. On average, peak horizontal velocity tended to occur close to seat-off (the Phase 1-

**Figure 11.** Representative plots of the horizontal and vertical components of the velocity of the whole body center of gravity vs. time for Group 1 (a), Group 2 (b), and Group 3 (c).

onents of the
), Group 2 (b),

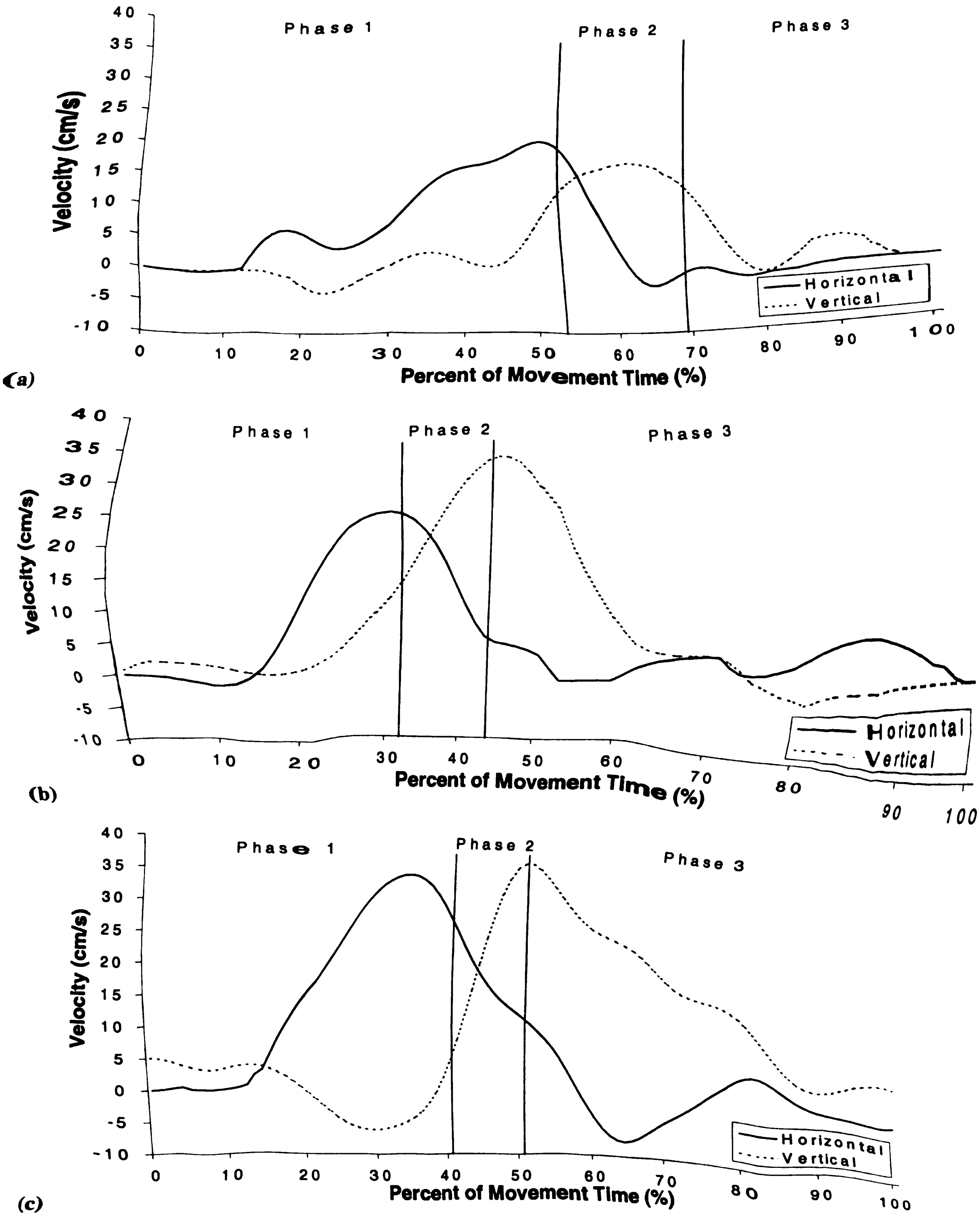



**Figure 11.**

Phase 2 transition point) for Groups 1 and 2. However, for Group 3 the peak horizontal velocity occurred about 10% of movement time prior to seat-off (see Figure 11). There was, however, considerable variability from trial to trial and subject to subject on the occurrence of peak horizontal velocity relative to seat-off. The timing of the peak vertical velocity occurred, on average, close to the Phase 2-Phase 3 transition point for Groups 2 and 3, but about 7% of movement time before this point for Group 1 (see Figure 11).

*Ground Reaction Forces at the Buttocks and the Feet*

In the present study the foot on the side of the body being videotaped was isolated so that only the forces and moments associated with that foot were measured; this facilitated the calculation of joint moments. However, virtually all of the ground reaction force data reported in the literature is for two feet measured with a single force platform. Therefore, in order to compare the results of the present study with those reported for adults and other children, symmetry was assumed and the values for a single foot was doubled to arrive at values representative of both feet.

During initial sitting subjects supported (on average) about 85% of total body weight on the buttocks and about 15% of total body weight on the feet. The STS movement was initiated by a posteriorly-directed, propulsive horizontal force from the buttocks followed shortly by a posteriorly-directed force of the feet. At about the same time as the posterior force at the feet was initiated there began a period of loading (vertical force) at the buttocks and unloading (vertical force) at the feet. Onset of vertical loading of the feet occurred well before seat-off (175 ms prior to seat-off, on average) and coincided with the onset of an anteriorly-directed, braking horizontal force at the feet

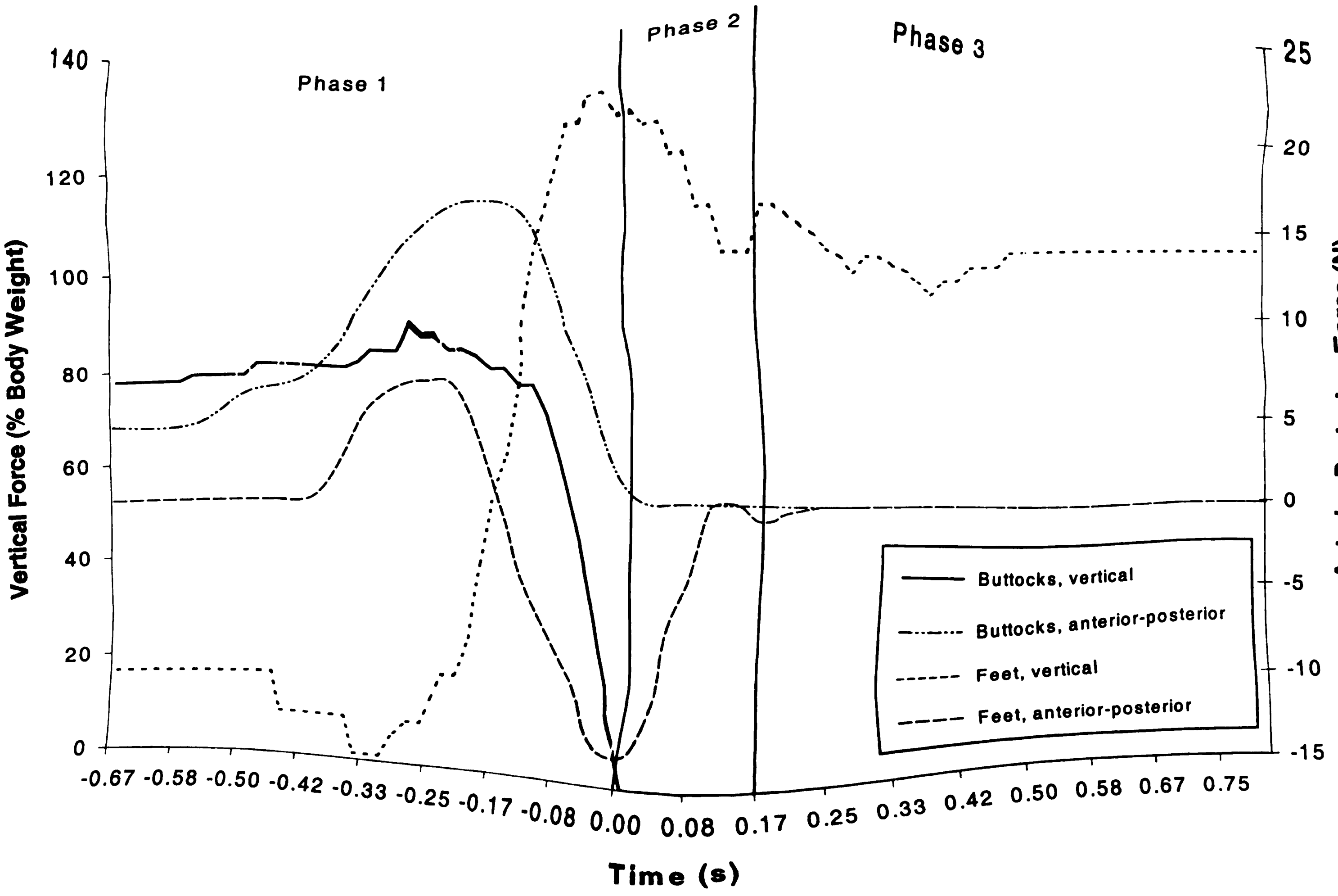


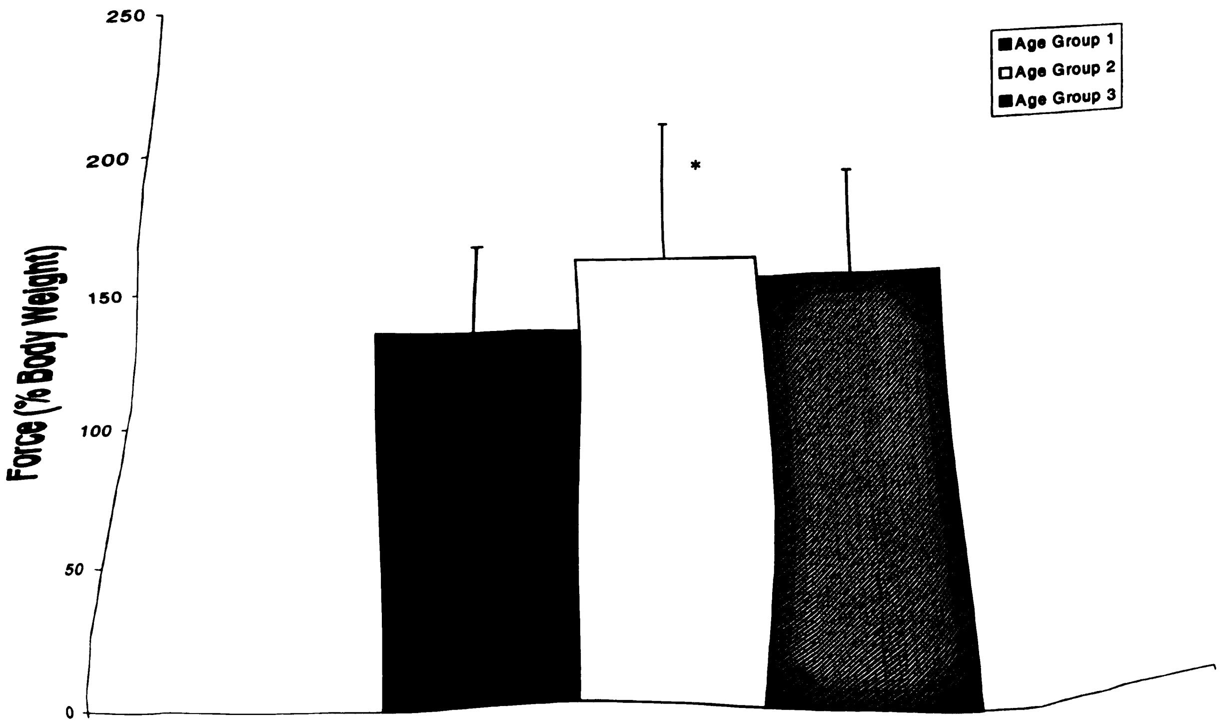

*Figure 12.* Representative plot of the vertical and anterior-posterior ground reaction forces at the buttocks and at the feet versus time.

which tended to peak around seat-off. An example of this pattern for a subject in Group 3 is shown in Figure 12.

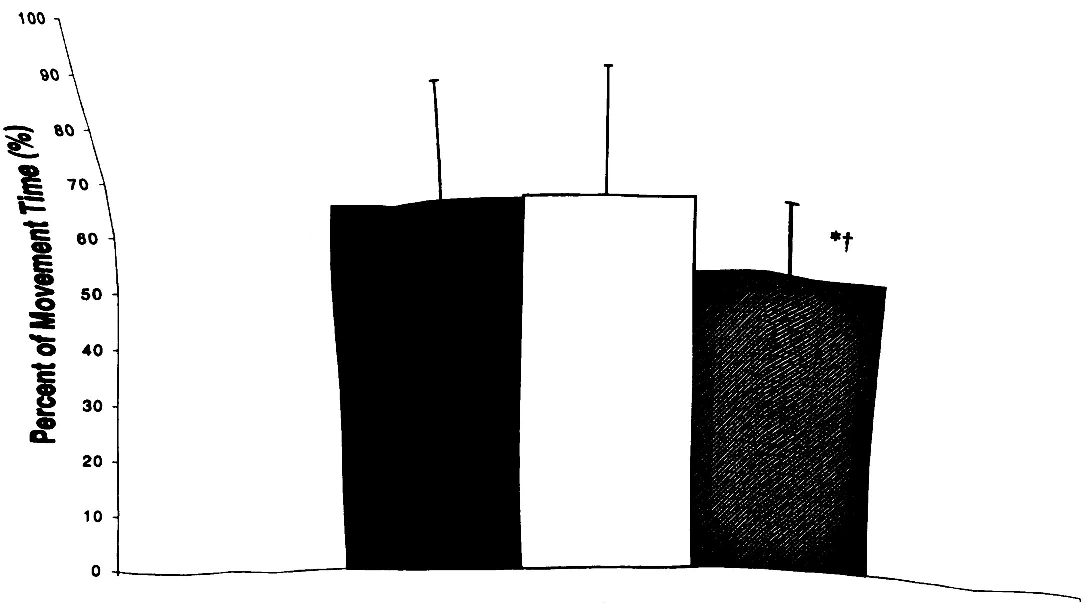
The mean peak vertical ground reaction force at the feet (GRFF)-normalized to body weight-and the mean time taken to reach the peak vertical GRFF (expressed as a percentage of total movement time) are shown in Figures 13a and b, respectively; the mean data for all subjects can be found in Table C5 in Appendix C. The mean peak GRFF for Group 1 (137 ±31% body weight) was significantly lower ($p < .01$) than for Group 2 (163 ±49% body weight), but was not significantly different from Group 3 (155 ±38% body weight); Groups 2 and 3 were not significantly different from each other. On the other hand, the mean time taken to reach peak GRFF was significantly less ($p < .01$) for Group 3 (53 ±13%) than for Groups 1 (66 ±21%) and 2 (67 ±23%), which were not significantly different from each other. For all groups, the mean peak GRFF occurred after seat-off, although it tended to occur closer to seat-off with increasing age (compare Tables C5 and C1).

## *Joint Moments*

The mean peak hip and knee moments are shown in Figure 14 (the mean data for all subjects can be found in Table C5 in Appendix C). Note that the moments were normalized by dividing by the subject's body weight (in newtons), multiplying by the subject's height (in meters), and then multiplying by 100. The mean normalized peak hip moment increased significantly ($p < .01$)with each subsequent age group (Group 1 = 9.0 ±6.6, Group 2 = 14.6 ±6.4, and Group 3 = 31.0 ±13.4). For the knee joint Group 3 again had the greatest mean normalized peak moment (15.2 ±5.4), and this was significantly




(a)

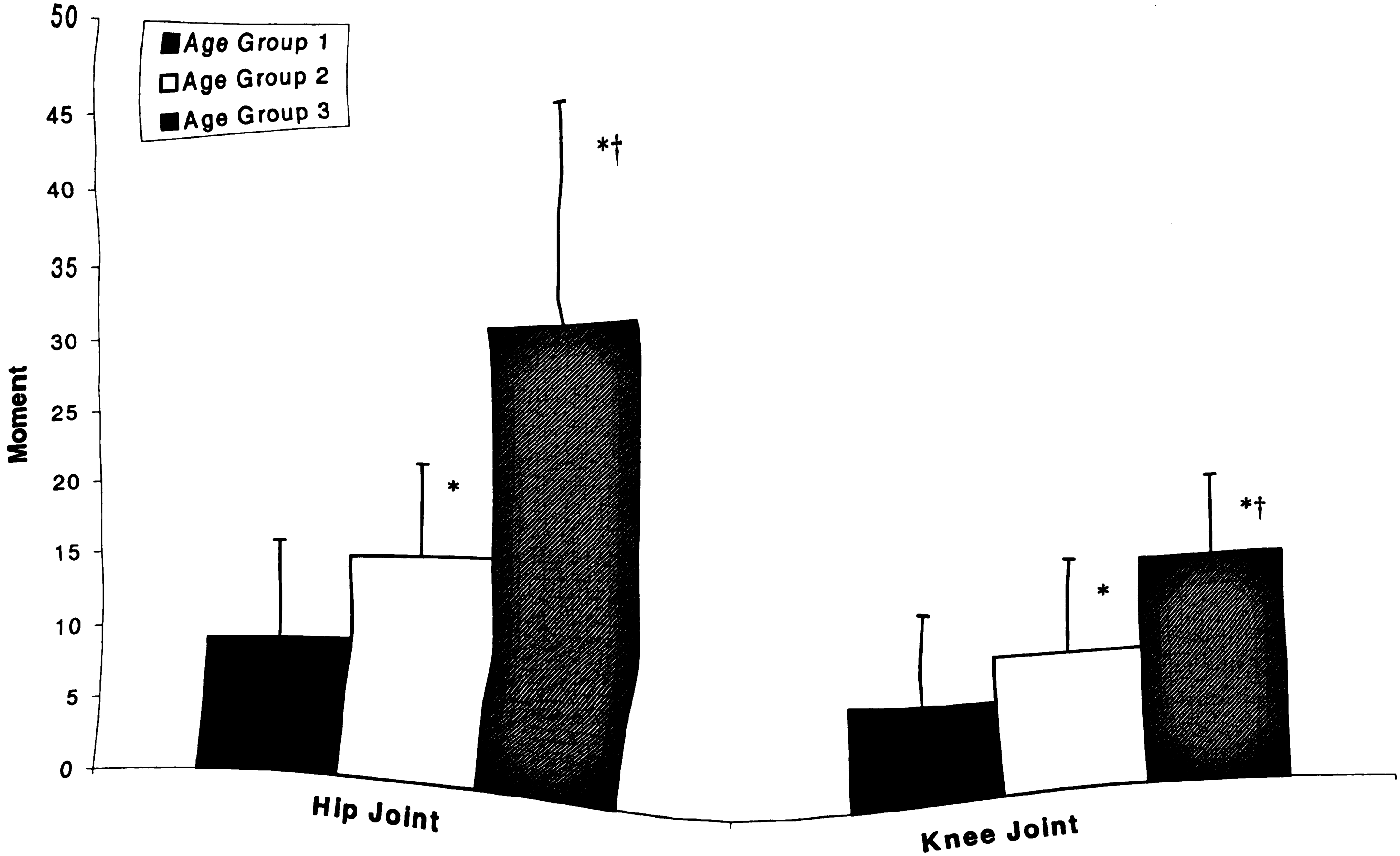



(b)

* Significantly different from Group 1 (p<.05)

† Significantly different from Group 2 (p<.05)

**Figure 13.** Mean (+ 1 s.d.) peak ground reaction force (GRF) at the feet (a) and the time to peak GRF at the feet as a percent of movement time (b) for the three age groups.




* Significantly different from Group 1 ($p$<.05)
† Significantly different from Group 2 ($p$<.05)

***Figure 14.*** *Mean (+ 1 s.d.) peak moment at the hip and knee joints for the three age groups.* Note that the moments were normalized by dividing by body weight (N), multiplying by height (m), and multiplying by 100.

greater ($p < .05$) than that for Groups 1 (6.2 ±5.8) and 2 (9.4 ±5.8). Group 2 also had a significantly greater ($p < .05$) mean normalized peak knee moment than Group 1.

# DISCUSSION

## *Movement and Phase Times*

As might be expected, movement time is the single most commonly reported result among all of the sit-to-stand studies. Likewise, the studies which divide the STS into phases usually provide a break down of the time required for each phase, typically expressed as a percentage of total movement time in order to normalize the data across subjects. In the present study subjects performed the STS at what is often termed a "normal," "self-selected," or "natural" speed. Thus comparison of movement times can only be made with those studies that did not control the speed of movement in some way. The total mean movement time for the entire group of subjects in the present study was 1.1 ±0.4 s. This result is similar to the 1.2 s found by Cahill, et al. (1999) for their entire group of children. The mean movement times reported by various authors for adult subjects for the STS performed at a natural speed is shown in Table 5. Those found for children in the present study and by Cahill, et al. are reported for comparison. (It should be noted that age ranges for the groups in Cahill, et al.'s study differ from those used in the current study, and were as follows: 1.1-1.5 years for Group 1, 4.1-5.0 years for Group 2, and 8.6-9.9 years for Group 3.) The range of movement times reported is relatively large (1.0-3.3 s), although most studies found times between 1.5 and 2.0 s. What is interesting is that the total movement times for young children as found in the present study and by Cahill, et al. are substantially less than those reported for adults. Since seat height in both studies was set at knee height (and thus normalized), seat height should not be a factor in movement time. One possible cause of the difference in movement times is

**Table 5.** Mean (±s.d. where reported) total movement time and, where applicable, duration of each phase as a percentage of total movement time reported by various authors (the age range of the subjects in each study is also reported for comparison).

| Study | Age Range (yr) | Movement Time (s) | Phase 1 (%) | Phase 2 (%) | Phase 3 (%) |
|---|---|---|---|---|---|
| Present study | | 1.1 (±0.4) | 53 (±10) | 16 (±11) | 31 (±17) |
| Group 1 | 1.0-1.5 | 1.2 (±0.3) | 55 (±11) | 20 (±12) | 25 (±17) |
| Group 2 | 2.0-3.0 | 0.9 (±0.2) | 56 (± 9) | 13 (±11) | 30 (±16) |
| Group 3 | 4.0-5.0 | 1.2 (±0.3) | 53 (±10) | 16 (±11) | 31 (±17) |
| Alexander, et al. (1991) | | | | | |
| Young adults | 19-31 | 1.6 (±0.2) | 38 (± 6) | | |
| Older adults | 63-86 | 1.6 (±0.4) | 42 (± 7) | | |
| Cahill, et al. (1999) | | | | | |
| Group 1 | 1.1-1.5 | 1.0 | | | |
| Group 2 | 4.1-5.0 | 1.2 | | | |
| Group 3 | 8.6-9.9 | 1.4 | | | |
| Hirschfeld, et al. (1999) | 20-28 | 1.5 (±0.2) | | | |
| Kotake, et al. (1993) | 22-40 | | 54. (± 4) | | |
| Kralj, et al. (1990) | 24-51 | | 21 | 24 | 55 |
| Millington, et al. (1992) | 65-76 | 3.3 (±0.6) | 33 (± 6) | | |
| Mourey, et al. (2000) | | 2.0 (±0.3) | | | |
| Young adults | 20-25 | 1.4 (±0.2) | | | |
| Older adults | 71-82 | 1.8 (±0.3) | | | |

Table 5. (cont'd)

| Study | Age Range (yr) | Movement Time (s) | Phase 1 (%) | Phase 2 (%) | Phase 3 (%) |
|---|---|---|---|---|---|
| Nuzik, et al. (1986) | 20-48 | 1.8 (±0.3) | | | |
| Pai, Naughton, et al. (1994) | | | | | |
| Young adults | 25-38 | 2.0 (±0.3) | 34 (± 4) | | |
| Older adults | 63-84 | 2.1 (±0.4) | 35 (± 3) | | |
| Pai & Rogers (1991b) | 26-38 | 1.6 (±0.2) | | | |
| Papa & Cappozzo (2000) | 22-34 | 1.6 (±0.3) | | | |
| Shepherd & Gentile (1994) | 20-30 | 1.5 | 46 | | |
| Vander Linden, et al. (1994) | 61-78 | 1.4 (±0.2) | 36 (± 4) | 19 (± 6) | 45 (± 5) |

that even though the adult subjects were asked to perform the STS at a natural speed, they may have performed the movement more self-consciously, and therefore more slowly. Another possibility is that the children (especially the younger children) were eager to stand up and move toward their parents and were thus likely to stand up as quickly as possible; Cahill, et al. reported similar behavior. Indeed, those studies that had subjects rise at a self-selected "fast" speed reported total movement times similar to those found in the present study and by Cahill, et al. (Mourey, et al., 2000: 1.0 s for young adults, 1.4 s for older adults; Pai, et al., 1994: 1.4 s; Pai & Rogers, 1991: 1.2 s; Papa & Cappozzo, 2000: 1.2 s).

Also shown in Table 5 are the mean durations (as a percentage of total movement time) of the three phases of the STS reported in the literature. As noted in the review of literature, there is no overall agreement on the definition of phases for the STS. Therefore the only durations reported in Table 5 are those for phases that could clearly be identified with one of the three phases used in the present study. Not surprisingly this could most easily be done for Phase 1, which ends at seat-off, an event that is clearly defined and reported in most studies. Unfortunately, the studies by Schenkman and colleagues (Ikeda, et al., 1991; Riley, et al., 1991; Schenkman, et al., 1990), from which the phase definitions for the present study were derived, could not be used for comparison because they controlled the movement speed of their subjects. The most noticeable difference between the children in the present study and adults is the amount of time spent in Phase 1 versus Phase 3. The children spent substantially longer in Phase 1 than did the adults, while the adults spent longer in Phase 3 (the only exception was Hirschfeld, et al., 1999, who reported a Phase 1 duration similar to that found for the children). On the whole, the duration for Phase 2 was not substantially different between children and adults. As a result, both the Phase1-Phase 2 and Phase 2-Phase3 transition points (i.e., seat-off and maximum ankle dorsiflexion, respectively) occurred later for the children. One possible cause for the greater amount of time the children spent in Phase 1 (the flexion-momentum phase) is that children may have more difficulty controlling the momentum of the upper body. Cahill, et al (1999) postulated this based on the fact that in their study total hip displacement (in flexion) and peak hip flexion velocity increased with increasing age. This same result was found in the present study (see Tables 6 and 7). Cahill, et al. suggest that this may be due to the proportionally greater mass of the head and trunk of children compared to adults. On the other hand, the values for peak hip flexion velocity and peak horizontal velocity of the body's center of gravity for the older children in the present study are similar to those found for adults. This suggests that control of momentum may not be the entire answer.

Another possibility is related to the fact that young children have proportionally longer torsos and shorter legs than adults (Malina & Bouchard, 1991). Therefore, relatively more time is needed by the children to move the trunk into optimal position compared to the time needed to extend the legs. A third possibility is more mundane: Hirschfeld, et al. (1999), who had a similar Phase 1 duration as the present study, argued that the later occurrence of seat-off in their study is due to the fact that seat-off was determined kinetically using a force plate beneath the buttocks (as in the present study) instead of kinematically. On the otherhand, Pai, Naughton, et al. (1994) also used a force plate beneath the buttocks but found seat-off to occur at roughly 40% of movement time.

*Joint Range of Motion*

Shown in Table 6 are the total ranges of motion at the ankle, knee, and hip joints reported for adults in various studies; the results of the present study are included for comparison. In comparison with the adults in the (relatively few) studies that reported total joint ranges of motion, the children in the present study had a greater range of motion at the ankle, a smaller range of motion at the knee, and a comparable range of motion at the hip. The range of motion of the knee joint is almost entirely dependent on the initial position of the knee joint while sitting and on how much the knee is extended by the end of the STS. That the children in the present study had a smaller range of motion at the knee is indicative of the fact that many of the children began the movement with their knees at less than 90° (i.e., more extended) and then flexed the knees to near 90° close to seat-off, and then finished the STS with their knees still slightly flexed (see Figure 6). On the other hand many adults began the STS with their knees flexed more than 90° and finished in full extension. That children finished with the knees slightly flexed may be due to a need to keep the center of gravity slightly lower in order to increase stability, or to the fact that many of the children almost immediately started to take a step at the completion of the STS, thus not fully extending the knees and hips. The greater range of motion at the ankle joint experienced by the children compared to the adults may be a result of increased postural sway due to a lack of postural control (Shumway-Cook & Woollacott, 1985). The fact that the children in Group 3 (4 to 5 years of age) had a greater ankle range of motion than the younger children is not inconsistent with this hypothesis, as Shumway-Cook and Woollacott suggest that this age is a transitional age in the development of postural control. Cahill, et al. (1999) suggest that a

**Table 6.** Mean (± s.d. where reported) joint range of motion, peak hip flexion angle, and time to peak hip flexion (expressed as a percentage of total movement time) reported by various authors (the age range of the subjects in each study is also reported for comparison).

| Study | Age Range (yr) | Ankle ROM (°) | Knee ROM (°) | Hip ROM (°) | Peak Hip Flexion (°) | Time to Peak (%) |
|---|---|---|---|---|---|---|
| Present study | | 35 (±13) | 68 (±21) | 97 (±20) | 114 (±15) | 40 (±10) |
| Group 1 | 1.0-1.5 | 29 (±12) | 61 (±16) | 90 (±17) | 110 (±13) | 38 (±12) |
| Group 2 | 2.0-3.0 | 25 (± 9) | 60 (±15) | 86 (±14) | 103 (±12) | 43 (± 8) |
| Group 3 | 4.0-5.0 | 35 (±14) | 83 (±22) | 113 (±16) | 127 (± 9) | 40 (± 6) |
| Alexander, et al. (1991) | 19-31 | | | | 127 (± 8) | |
| Cahill, et al. (1999) | | | | | | |
| Group 1 | 1.1-1.5 | | | | 112 (± 6) | 33 (±10) |
| Group 2 | 4.1-5.0 | | | | 120 (± 6) | 31 (± 7) |
| Group 3 | 8.6-9.9 | | | | 124 (± 6) | 32 (± 5) |
| Doorenbosch, et al. (1994) | 23-31 | | | | 93 (± 8) | 40 |
| Hirschfeld, et al. (1999) | 20-28 | | | | 120 (± 5) | |
| Ikeda, et al. (1991) | | | | | | |
| Young adults | 25-36 | 20 (± 4) | 106 (± 8) | 105 (±12) | 101 (± 9) | |
| Older adults | 61-74 | 18 (± 8) | 100 (± 8) | 106 (± 8) | 98 (± 9) | |
| Millington, et al. (1992) | 65-76 | | | | | |
| Nuzik, et al (1986) | 20-48 | | | | 95 (± 9) | 34 (± 3) |
| Pai & Rogers (1991b) | 26-38 | 12 | 84 | 73 | 102 | |
| | | | | | 100 | 38 |

**Table 6.** (cont'd.)

| Study | Age Range (yr) | Ankle ROM (°) | Knee ROM (°) | Hip ROM (°) | Peak Hip Flexion (°) | Time to Peak (%) |
|---|---|---|---|---|---|---|
| Schenkman, et al. (1990) | 25-36 | | | | 104 (±12) | 36 |
| Shepherd & Gentile (1994) | 20-30 | | | | 119 (± 9) | |
| Vander Linden, et al. (1994) | 61-78 | 22 (± 3) | 96 (± 8) | 99 (±14) | | |

lack of postural control may also be a cause of the greater variability in performance evidenced by 4- and 5-year-old children compared to adults and 9- and 10-year-old children. Interestingly, the 4- and 5-year-old children in the present study had the smallest amount of variability in total movement time.

In addition to the ranges of motion of various joints, many authors also report the peak hip flexion angle during the STS (in fact, more studies report the peak hip flexion angle than ranges of motion). The reason for this is that the maximum amount of hip flexion indicates the amount of forward lean of the head and trunk (HAT) and is related to the most anterior position of the center of gravity. This latter position is also dependent on the maximum amount of ankle dorsiflexion. These values, as well as the time to peak hip flexion angle expressed as a percentage of total movement time, are shown in Table 6. In comparison with the children in the study by Cahill, et al. (1999; see Table 6) the subjects in the present study had similar peak hip flexion angles. In addition, the same trend of increasing hip flexion angle with increasing age reported by Cahill, et al. was also found in the present study, but only for Groups 1 and 2 in relation to Group 3; the value for Group 2 was actually significantly less than that for Group 1. What are the possible explanations for the relationship between Groups 1 and 2? One is that there is no real relationship between peak hip flexion angle and age, but that the significant differences are simply due to variability from one age to the next. Evidence for this explanation may be found in the range of peak hip flexion angles reported in the literature for adult subjects (see Table 6). Another possibility, however, is related to the relationship between peak hip flexion angle and movement speed: Namely, that (for the same subject) the amount of hip flexion tends to decrease as movement speed increases

(Papa & Cappozzo, 2000; Vander Linden, 1994). It is possible, therefore, that the smaller peak hip flexion angle for Group 2 is due in part to their significantly faster total movement time (see Table C 1). Likewise, the increase in peak hip flexion angle with increasing age found by Cahill, et al. may be due in part to the fact that movement time also increased (i.e., movement speed decreased) with age.

In the present study the time to peak hip flexion ranged from 30 to 47% of total movement time, which is comparable to the times reported in the literature for both children and adults (see Table 6). In addition, the time to peak hip flexion for children varied little with age, both in the present study and in the study by Cahill, et al. (1999).[1] In the present study peak hip flexion was consistently reached before seat-off occurred (i.e., in Phase 1; compare Tables 5 and 6). Interestingly, this result is in contrast with those found by Schenkman and colleagues (Ikeda, et al., 1991; Riley, et al., 1991; Schenkman, et al., 1990) for both younger and older adults in which peak hip flexion occurred slightly after seat-off.

*Peak Joint Angular Velocities*

The STS movement largely involves movement at the hip and knee joints, and to a lesser extent, the ankle joint. One variable of interest therefore is the maximum velocity attained during the movement at the joints involved. Particularly, the maximum velocity

[1] It should be noted that in the present study the time for Group 1 was just significantly less than that for Group 2, while neither of these groups was significantly different from Group 3. It is questionable, however, whether the statistically significant difference between Group 1 and Group 2 is biomechanically significant.

for both hip flexion (which occurs during the first part of the movement) and hip extension (which occurs during the latter part of the movement) as well as knee extension (little knee flexion occurs once the movement is initiated). Also of interest are the times at which these maxima are reached. Table 7 shows the peak hip flexion, hip extension, and knee extension velocities-as well as the times at which these peaks occurred (as a percentage of movement time)-found in the present study; data for some of these variables reported by Cahill, et al. (1999) for children and by four other authors for adults are also reported for comparison. The most commonly reported variable was peak hip flexion velocity. The values found in the present study for peak hip flexion velocity were comparable to those reported by Cahill, et al. for children, and by Ikeda, et al. (1991) and Shepherd and Gentile (1994) for adults, although the velocities found by the author and by Cahill, et al. for the older children were greater than those found by Ikeda, et al. and Shepherd and Gentile. Roebroeck, et al. (1994) reported a peak hip flexion velocity of 48°/s which is well below that found in any other study. Their reported values for peak hip and knee extension velocities were also below those found in the present study and those reported by Ikeda, et al.. The reason for this low value is probably due to the fact that Roebroeck, et al. set the movement speed at 23 cycles per minute (equivalent to a movement speed of 2.3 s), slower than the "natural" movement times found in all the other studies reported in Table 5 with the exception of Kralj, et al. (1990) who reported a movement time of 3.3 s. Likewise, the relatively faster movement times found in the present study and reported by Cahill, et al. may be the reason why the velocities in these studies were greater than those

**Table 7.** Mean (± s.d. where reported) peak hip flexion velocity (hipflexv), hip extension velocity (hipextv), and knee extension velocity (kneeextvel); and time to peak hip flexion (thfv), hip extension (thev), and knee extension (tkev) velocities (expressed as a percentage of total movement time), reported by various authors (the age range of the subjects in each study is also reported for comparison).

| Study | Age Range (yr) | hipflexv (°/s) | hipextv (°/s) | kneeextv (°/s) | thfv (%) | thev (%) | tkev (%) |
|---|---|---|---|---|---|---|---|
| Present study | | 84 (±37) | 243 (±81) | 180 (±75) | 23 (±10) | 75 (±11) | 75 (±13) |
| Group 1 | 1.0-1.5 | 64 (±24) | 206 (±68) | 143 (±62) | 18 (±12) | 75 (±11) | 74 (±14) |
| Group 2 | 2.0-3.0 | 89 (±25) | 278 (±77) | 208 (±73) | 26 (± 9) | 72 (±12) | 72 (±12) |
| Group 3 | 4.0-5.0 | 105 (±46) | 264 (±82) | 206 (±73) | 25 (± 6) | 76 (±11) | 77 (±13) |
| Cahill, et al. (1999) | | | | | | | |
| Group 1 | 1.1-1.5 | 69 (±23) | | | | | |
| Group 2 | 4.1-5.0 | 80 (±23) | | | | | |
| Group 3 | 8.6-9.9 | 92 (±12) | | | | | |
| Ikeda, et al. (1991) | | | | | | | |
| Younger adults | 25-36 | 74 (±16) | 162 (±27) | 150 (±28) | | | |
| Older adults | 61-74 | 72 (±21) | 156 (±39) | 157 (±35) | | | |
| Roebroeck, et al. (1994) | 23-35 | 48 | 100 | 88 | 23 | 60 | 64 |
| Schenkman, et al. (1990) | 25-36 | | | | 17 | 73 | 80 |
| Shepherd & Gentile (1994) | 20-30 | 75 (±17) | | | | | |

reported elsewhere.[2] In addition, the same trend of increasing peak *hip flexion* velocity with increasing age in children reported by Cahill, et al. was found in the present study. However, whereas Cahill, et al. found the increase to be significant across all three age groups, in the present study the differences between Group 1 and Group 2 and between Group 1 and Group 3 were significant, but the difference between Group 2 and Group 3 was not.

As far as the timing of the peak velocities is concerned, only Roebroeck, et al. (1994) and Schenkman, et al. (1990) reported values. The timing of the peak hip flexion velocity in the present study corresponded well with that found in the study by Roebroeck, et al, but was slightly later than that reported by Schenkman, et al.. On the other hand, the timing of the peak hip and knee extension velocities in the present study was comparable to those in the study by Schenkman, et al., but occurred later than that reported by Roebroeck, et al.. As was the case for Schenkman, et al., the peak hip flexion velocity occurred in Phase 1 and the peak hip and knee extension velocities occurred in Phase 3.

*Velocity, Momentum, and Kinetic Energy of the Whole-body Center of Gravity*

Several studies on adults (see Table 8) have investigated the velocity profile of the body's center of gravity (CG), typically looking at the horizontal (anterior-posterior) and vertical components of the velocity of the CG. In addition, some authors have studied the

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[2] However, it should be noted that in the present study the correlation between hip flexion velocity and movement time was low (-.174); this is unlike the correlations between hip extension velocity and movement time, and between knee extension velocity and movement time, which were moderate (-.548 and -.510, respectively).

**Table 8.** Mean (± s.d. where reported) horizontal and vertical components of the peak velocity of the whole body center of gravity, as well as the time to peak horizontal (tcghor) and vertical (tcgvert) velocities of the center of gravity (expressed as a percentage of total movement time), reported by various authors (the age range of the subjects in each study is also reported); the time at seat-off (tso) is also included for comparison.

| Study | Age Range (yr) | CG vel., hor. (cm/s) | CG vel., vert. (cm/s) | tcghor (%) | tcgvert (%) | tso (%) |
|---|---|---|---|---|---|---|
| Present study | | 30.2 (±15.3) | 28.8 (±12.9) | 51 (±22) | 68 (±14) | 53 (±10) |
| Group 1 | 1.0-1.5 | 22.5 (±14.5) | 19.4 (± 7.5) | 57 (±27) | 68 (±15) | 55 (±11) |
| Group 2 | 2.0-3.0 | 33.9 (±10.7) | 33.4 (± 7.6) | 56 (±17) | 71 (±13) | 56 (± 9) |
| Group 3 | 4.0-5.0 | 37.0 (±15.2) | 37.0 (±13.9) | 40 (±14) | 65 (±14) | 49 (± 9) |
| Hirschfeld, et al. (1999) | 20-28 | 53.0 (± 8.0) | | 41 (± 3) | 67 (± 5) | 54 (± 4) |
| Pai, Naughton, et al. (1994) | | | | | | |
| Younger adults | 25-38 | 50.8 (±10.8) | 70.9 (±16.9) | 30 (± 4) | 50 (± 4) | 34 (± 4) |
| Older adults | 63-84 | 45.6 (±15.7) | 47.0 (±15.7) | 31 (± 3) | 54 (± 4) | 35 (± 3) |
| Pai & Rogers (1990) | 26-38 | 54.5 | 68.1 | 28 (± 4) | 52 (± 8) | 36 (± 5) |
| Riley, et al. (1991) | 25-36 | 58.0 | 65.0 | 34 | 66 | 35 |
| Roebroeck, et al. (1994) | 23-35 | 32.0 | 35.0 | 28 | 50 | 35 |
| Vander Linden, et al. (1994) | 61-78 | | | 29 (± 4) | 64 (± 8) | 36 (± 4) |
| Yu, et al. (2000) | 24-38 | 61.0 (±10.0) | 39.0 (± 4.0) | 29 | 62 | |

linear momentum of the CG (Pai, Naughton, et al., 1994; Pai & Rogers, 1990a; Riley, et al., 1991) and one study investigated the kinetic energy of the CG (Riley, et al. 1991). There is, of course, a direct relationship among velocity, momentum, and kinetic energy. Namely, momentum is equal to mass times velocity and kinetic energy is equal to one-half the mass times velocity squared. Thus, as might be expected, the velocity, momentum, and kinetic energy of the STS have similar patterns; it is only the magnitude of each that varies. In fact, velocity allows for better comparison between subjects because it is "normalized" by its very nature. That is to say, in order to normalize momentum or kinetic energy we would typically divide by body mass, which leaves us with velocity as a normalized momentum and one-half the velocity squared as a normalized kinetic energy. For this reason, Table 8 (and Table C4 before it) reports only the peak velocity of the CG (broken down into its horizontal and vertical components) for the aforementioned studies, although the discussion below will include the momentum and kinetic energy of the CG. The time taken to reach the peak horizontal and vertical velocities, as well as the time to seat-off, is also shown in Table 8; the times are expressed as a percentage of total movement time.

Compared to adults, several things can be noted about the velocity of the CG for the children in the present study. First, the peak horizontal and vertical velocities of the CG were substantially lower for the children versus the adults, with the exception of those in the study by Roebroeck, et al. (1994). In this case the low velocities are probably due to the slow movement times in that study (see above). In the present study, however, the movement times were comparable to, and often faster than, the times in these adult studies. The lower peak velocities seen in the children may be related to the lack of postural control noted earlier. Indeed, that peak horizontal and vertical velocities increased with increasing age (although only Group 1 was significantly different than the others; Groups 2 and 3 were not significantly different from each other) suggests that with increasing motor development and postural control peak velocities can be increased as well. Further evidence of this may be found in the increased joint velocities with increasing age noted above.

Second, for the adults the peak vertical velocity was greater than the peak horizontal velocity, whereas for the children the peak horizontal and vertical velocities were close in magnitude to one another, with the peak vertical velocity being generally slightly less than the peak horizontal velocity.

Third, the peak horizontal velocity occurred, on average, before the peak vertical velocity for both the adults and the children. However, the peak horizontal and vertical velocities tended to occur sooner for the adults versus the children, though it should be noted that times for the children in Group 3 were similar to those reported by Hirschfeld, et al. (1999) and Riley, et al. (1991). This timing may be related to the postural control issue: If the children had more difficulty controlling their upper body movement they might be expected to take longer to reach their peak horizontal velocity; this would in turn delay the peak vertical velocity. The older children in Group 3 did in fact reach peak horizontal velocity faster than the younger children, which would be expected if time to peak horizontal velocity is related to motor development. Interestingly though, the time to peak vertical velocity changed little from age group to age group. So perhaps although the older Group 3 children could generate a greater horizontal velocity in a shorter amount of time, they required a longer braking period and thus the time to *peak vertical velocity* remained almost unchanged.

Fourth, all of the adult studies found the peak horizontal velocity to occur before seat-off, although how much before seat-off varied form one study to the next. For instance, Riley, et al. (1991) found the peak horizontal velocity to occur very close to seat-off (34 versus 36% of movement time), whereas in the study by Hirschfeld, et al. (1999) it occurred at 41% of the movement time but seat-off not until 54%. The children in the present study showed similar variability. The mean peak horizontal velocity for the children in Group 1 actually occurred after seat-off, but this was largely due to Subject 5; all of the other children reached peak horizontal velocity prior to seat-off (see Table C4). On average the children in Groups 2 and 3 reached peak horizontal velocity before seat-off (although for one subject in Group 2 it occurred after seat-off), but whereas for Group 2 as a whole peak horizontal velocity occurred close to seat-off (the same was true for Group 1 as whole), it occurred substantially prior to seat-off for Group 3.

Finally, Riley, et al. (1991) found the peak vertical velocity to occur close to the Phase 2-Phase 3 transition point. This was true for the present study for the children in Groups 2 and 3, but the peak vertical velocity occurred well before the Phase 2-Phase 3 transition point for the children in Group 1. The Phase 2-Phase 3 transition point is the point of maximum dorsiflexion of the ankle, which represents the most forward rotation of the body over the ankle joint. It would fit that the youngest children who presumably have the least postural control would still be rotating forward even as they reach peak vertical velocity.

As noted above, the velocity of the CG is directly related to the linear momentum of the CG and its kinetic energy during the movement. Pai and colleagues (Pai, Naughton, et al, 1994; Pai & Rogers, 1990a) and Riley, et al. (1991) have examined in detail the linear momentum of the CG during the STS movement. The pattern of the horizontal and vertical CG velocity curves (and thereby the momentum curves) found in the present study (see Figure 11) was similar to that found by the above-named authors, differing only in relative magnitude and the time between peaks. This relationship is one in which the vertical velocity (and momentum) of the CG is at its lowest point close to the peak horizontal velocity of the CG. Then as the horizontal velocity decreases the vertical velocity increases until it reaches its peak. Riley, et al. found that the beginning of the increase in the vertical velocity corresponded almost exactly with the peak horizontal velocity. Pai and Rogers (1990a) found that the beginning of the rise in vertical velocity always occurred close to the peak horizontal velocity, but at faster movement speeds actually began before the peak horizontal velocity was reached. A similar result was found in the present study. Figure 15 shows the horizontal and vertical velocity of the CG versus time for two trials of different movement speeds. The upper graph (Figure 15a) is of a relatively slower trial (movement speed equal to 1.6 s), while the lower graph (Figure 15b) is of a relatively faster trial (movement time equal to 0.9 s).

Riley, et al. (1991) also examined the resultant kinetic energy pattern of the CG and found two kinetic energy peaks corresponding to the peak horizontal and peak vertical velocities, respectively, and a relative kinetic energy minimum occurring between these two peaks. Figure 16 shows a similar pattern for the trial shown in Figure 15a. Riley, et al. suggest that the kinetic energy pattern and the relationship between the

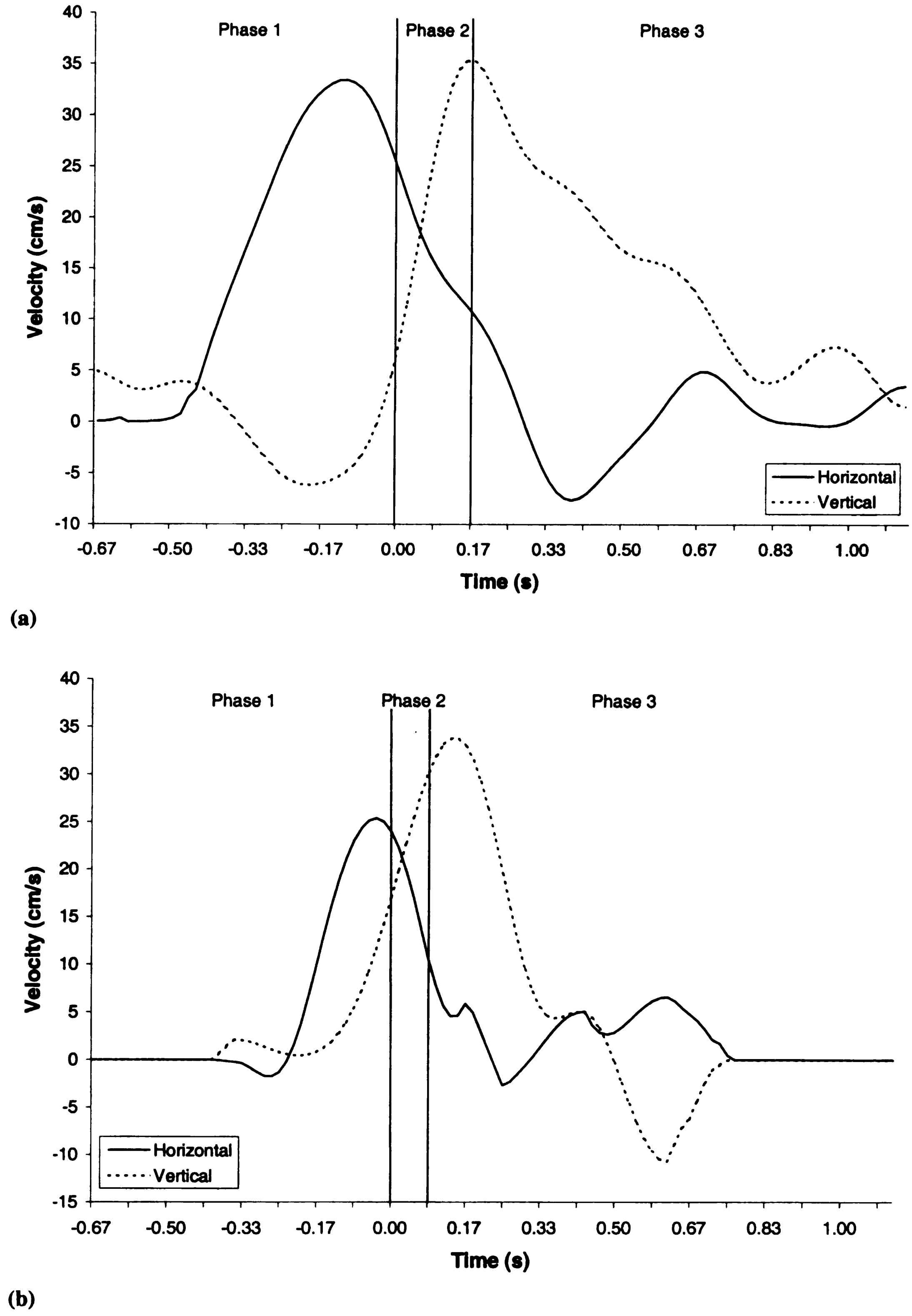



**Figure 15.** Plot of the horizontal and vertical velocities of the whole body center of gravity versus time for a relatively slow (a) and a relatively fast (b) trial.

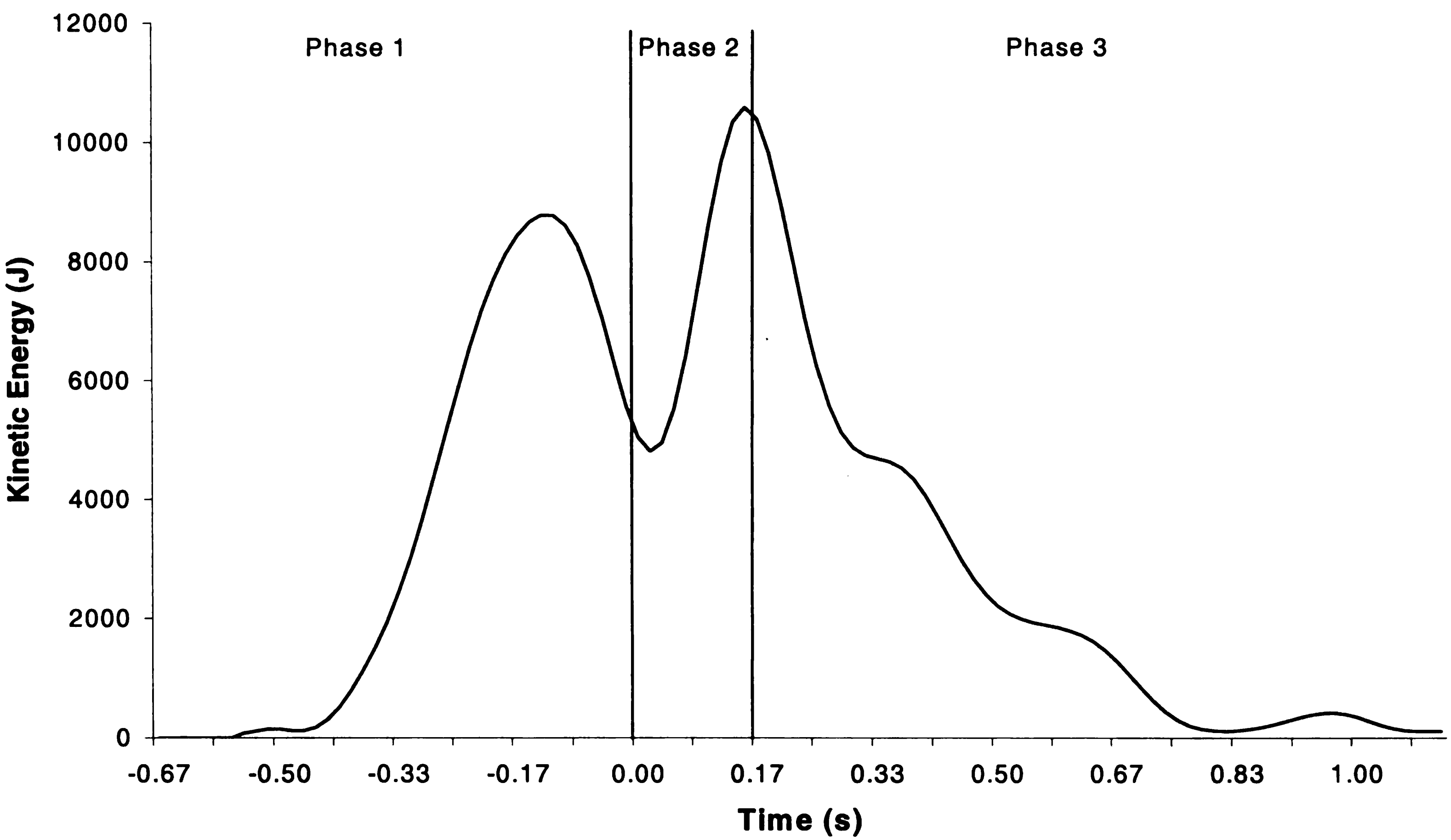



**Figure 16.** Representative plot of the kinetic energy of the whole-body center of gravity versus time. The center of gravity velocity profile for this trial is shown in Figure 15a.

horizontal and vertical velocities points to a transfer of kinetic energy and momentum from the upper body to the lower body during Phase 2 (aptly named the "momentum transfer phase"). The similar results found in the present study suggest that the same is true for children.

### *Ground Reaction Forces at the Buttocks and the Feet*

#### *Types of Forces*

There are three types of forces involved in the STS movement: (1) a posteriorly-directed, horizontal force from both the buttocks and the feet which generates a propulsive impulse and forward momentum; (2) an anteriorly-directed, horizontal force from the feet which generates a braking impulse to stop forward velocity; and (3) a vertical force from the feet which generates a vertical impulse and vertical velocity (see Figure 12). The type of pattern shown in Figure 12 has also been found for adults by Hirschfeld, et al. (1999). Magnan, et al. (1996), and by Pai and colleagues (Pai, Naughton, et al., 1994; Pai & Rogers, 1990). Whereas Hirschfield, et al. and Pai, Naughton, et al. found the feet to have generated only a small, if not negligible, propulsive impulse, in the present study the feet made a significant contribution (about 5% of body weight) to forward momentum. This result is, however, in agreement with Magnan, et al. who also found a propulsive impulse of similar magnitude to have been generated by the feet. It should also be mentioned when considering the horizontal forces generated by the feet that if a subject moved immediately from the STS to walking (as was the case for some of the younger children), and the stance leg was the one in contact with the force platform, there was a transition from the braking impulse to a second

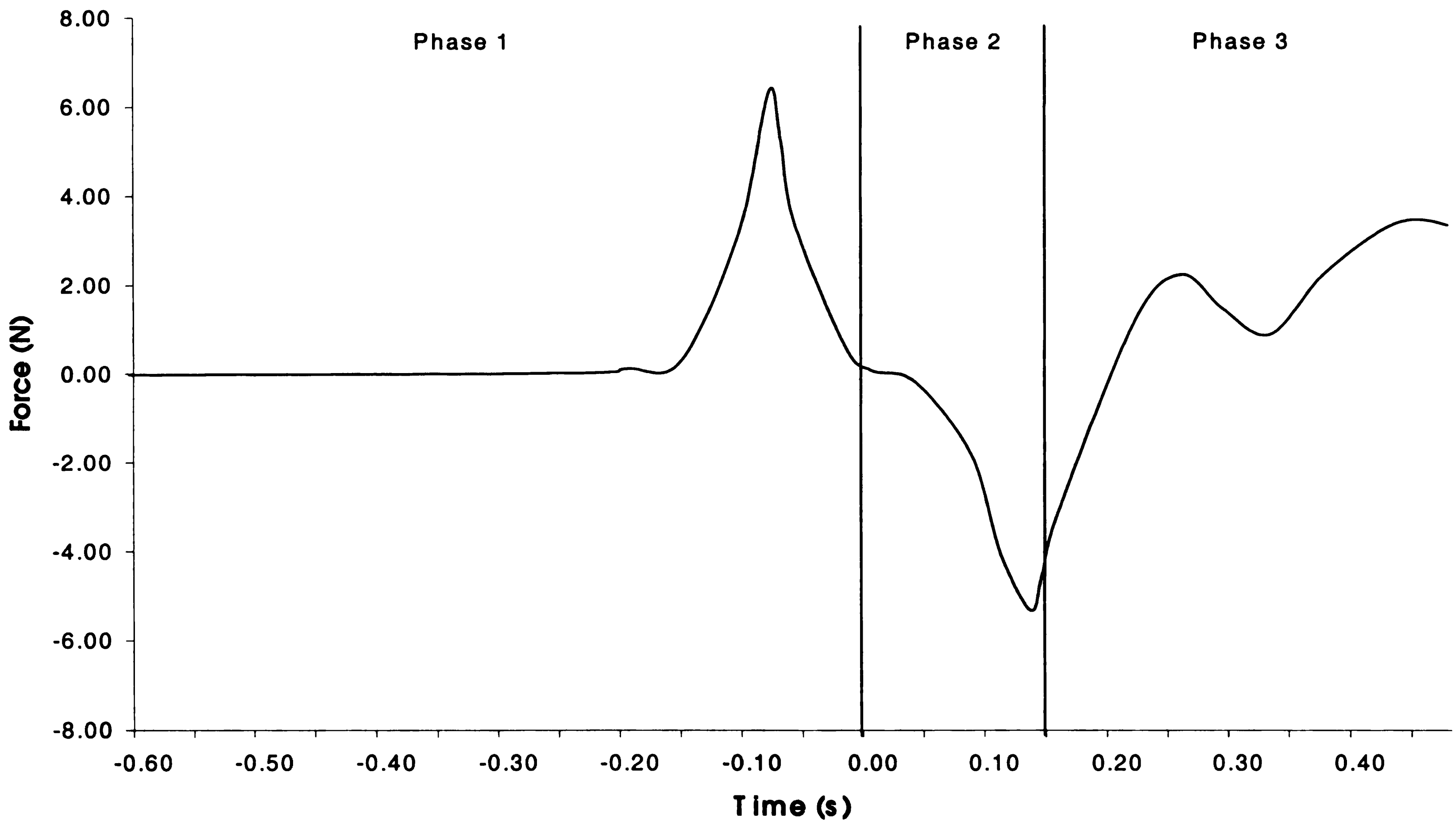



**Figure 17.** Plot of the anterior-posterior ground reaction force at the feet vs. time for a trial in which the subject initiated gait immediately from the sit-to-stand movement.

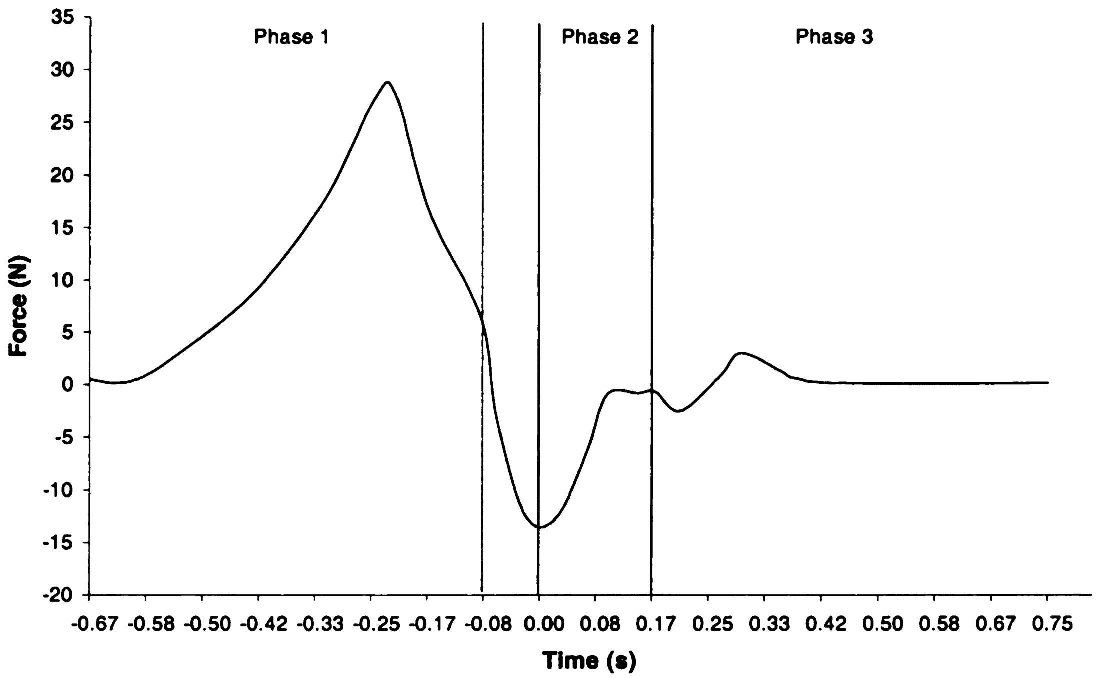
propulsive impulse (see, for example, Figure 17). This is consistent with the results reported by Magnan, et al. for the "sit-to-walk" movement.

*Horizontal Momentum and Horizontal Forces*

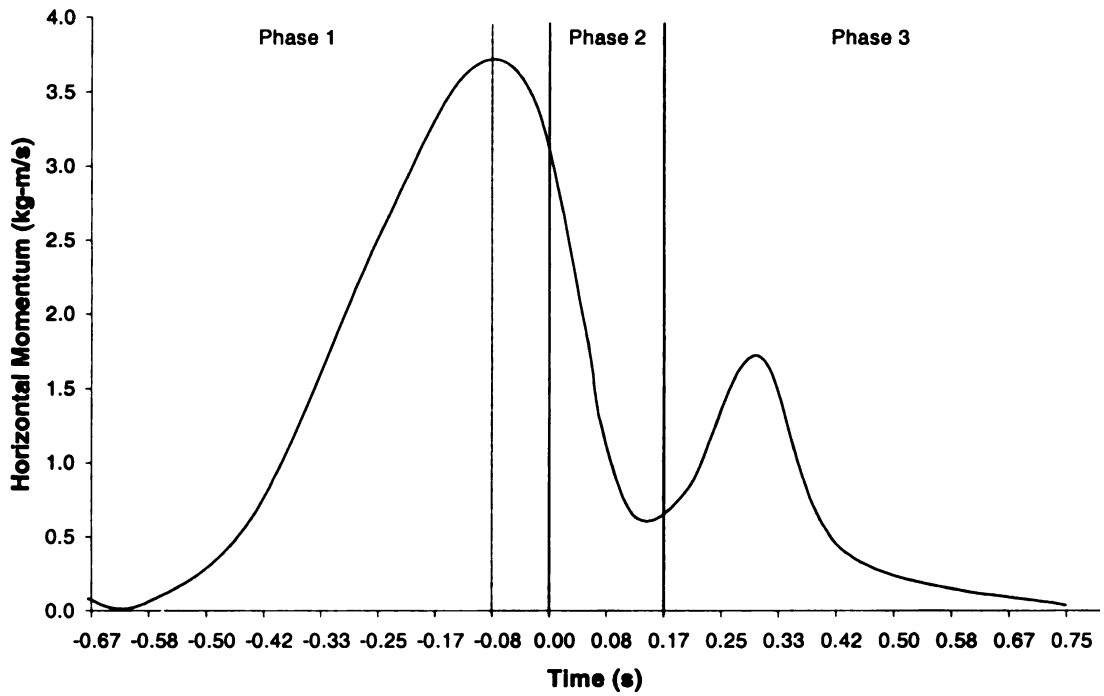
Also of interest is the relationship between the horizontal velocity/momentum of the body and the horizontal forces generated by the buttocks and the feet. In the STS movement the maximum horizontal momentum is due to, and equal to, the propulsive impulse (i.e., the area under the horizontal force vs. time curve). In the present study the transition from a propulsive to a braking impulse occurred close to the time of peak horizontal momentum (compare Figures 18a and b; in both figures the vertical bar indicates the occurrence of the peak horizontal momentum). Pai and colleagues (Pai, Naughton, et al., 1994; Pai & Rogers, 1990a) and Magnan, et al. (1996) found a similar correspondence between the time at peak horizontal momentum and the time at the transition from a propulsive to a braking impulse. Furthermore, in the present study the peak braking force occurred close to seat-off (i.e., time zero; see Figure 18a), a result which is also consistent with that found by Magnan, et al..

*Amplitude of the Peak Vertical Ground Reaction Force at the Feet*

In the present study the peak vertical ground reaction force from the feet (GRFF) was, on average, 150% of body weight for the entire group of subjects, but there was considerable variation from subject to subject, and within subject from trial to trial. There were not overly large differences in the peak vertical GRFF from age group to age group, although it was significantly less for Group 1 vs. Group 2 (see Table C5). The values




(a)




(b)

**Figure 18.** Plots for a single trial of (a) the resultant (i.e., of the buttocks and feet) anterior-posterior force versus time and (b) the horizontal momentum of the center of gravity versus time. The dotted vertical line indicates the time at peak horizontal momentum.

**Table 9.** Mean (± s.d. where reported) peak vertical ground reaction force at the feet (GRFF) normalized per body weight, time to peak vertical GRFF (expressed as a percentage of total movement time), peak normalized hip moment (Hip M), and peak normalized knee moment (Knee M) reported by various authors (the age range of the subjects in each study is also reported for comparison). The moments were normalized by dividing by weight (N), multiplying by height (m), and multiplying by 100.

| Study | Age Range (yr) | Peak GRFF (% BW) | Time to Peak GRFF (%) | Peak Hip M | Peak Knee M |
|---|---|---|---|---|---|
| Present study | | 150 (±40) | 62 (±20) | 17.8 (±13.6) | 10.0 (± 6.8) |
| Group 1 | 1.0-1.5 | 137 (±31) | 66 (±21) | 9.0 (± 6.6) | 6.2 (± 5.8) |
| Group 2 | 2.0-3.0 | 163 (±49) | 67 (±23) | 14.6 (± 6.4) | 9.4 (± 5.8) |
| Group 3 | 4.0-5.0 | 155 (±38) | 53 (±13) | 31.0 (±13.4) | 15.2 (± 5.4) |
| Cahill, et al. (1999) | | | | | |
| Group 1 | 1.1-1.5 | | | | |
| Group 2 | 4.1-5.0 | 117 (± 9) | | | |
| Group 3 | 8.6-9.9 | 124 (± 5) | | | |
| Doorenbosch, et al. (1994) | 23-31 | | | 10.8 | 14.4 |
| Hirschfeld, et al. (1999) | 20-28 | 104 (±14) | 51 (± 2) | | |
| Ikeda, et al. (1991) | | | | | |
| Young adults | 25-36 | | | 17.1 (± 3.6) | 19.2 (± 3.2) |
| Older adults | 61-74 | | | 16.1 (± 3.3) | 20.6 (± 3.6) |
| Magnan, et al. (1996) | 20-35 | 122 (± 5) | | | |
| Millington, et al. (1992) | 65-76 | 111 (± 4) | 39 (± 3) | | |
| Pai & Rogers (1991b) | 26-38 | | | 20.8 (± 6.9) | 38.7 (±12.5) |

**Table 9.** (cont'd.)

| Study | Age Range (yr) | Peak GRFF (% BW) | Time to Peak GRFF (%) | Peak Hip M | Peak Knee M |
|---|---|---|---|---|---|
| Roebroeck, et al. (1994) | 23-35 | | | 35.0 | 47.0 |
| Shepherd & Gentile (1994) | 20-30 | | | 39.8 (±13.2) | 19.3 (±14.1) |
| Vander Linden, et al. (1994) | 61-78 | 115 (± 8) | 42 (± 8) | | |

obtained in the current study for the peak vertical GRFF were consistently higher than those found for other children by Cahill, et al. (1999) and for adults by various authors (see Table 9). One possible reason for the relatively high peak vertical GRFFs found in the current study is the relatively fast movement times for subjects in the present study versus those in other studies (see Table 5), the theory being that a faster movement would require (or at least elicit) a greater peak vertical GRFF. This is similar to the argument made above for the relationship between movement speed and peak joint angular velocities. However, for the subjects in the present study the correlation between the peak vertical GRFF and movement time, though significant, was only slight ($r = -0.219$). Thus the higher peak vertical GRFFs in the current study may be due in part to the faster movement times, but also to other unknown factors.

*Timing of the Peak Vertical Ground Reaction Force at the Feet*

In the current study the peak vertical ground reaction force from the feet (GRFF) occurred, on average, at about 62% of total movement time for the entire group (see Table 9). Thus the peak vertical force was reached approximately 9% of movement time, or 100 ms, after seat-off. The older children in Group 3 reached their peak force significantly faster than Groups 1 and 2 (53% vs. about 66% of movement time), and their peak force occurred closer to seat-off (approximately 5% vs. 10% of movement time closer). These results are similar to those obtained for children by Cahill, et al. (1999; see Table 9): They found that the peak vertical force occurred at 124 ms after seat-off for children 4.1-5.0 years of age (comparable to Group 3 subjects in the current study) and 85 ms after seat off for children 8.6-9.9 years of age. Thus the peak vertical force tended to occur closer to seat-off with increasing age. It is interesting to note that overall, the children in the present study tended to reach their peak vertical force closer to seat-off than those of similar age in the study by Cahill, et al. Unfortunately, Cahill, et al. did not report the timing of seat-off, so it is impossible to compare their results to those of the present study based on percent of movement time. The timing of the peak vertical GRFF reported by several authors for adults is also shown in Table 9. These results tend to support the notion that the peak vertical force occurs sooner with increasing age, with Millington, et al. (1992) and Vander Linden, et al. (1994) having reported a time-to-peak of about 40% of movement time, substantially faster than those found in the present study. Interestingly, though, Hirschfeld, et al. (1999) found a time-to-peak to be 51% of movement time, not much different than that for the Group 3 subjects in the current study.

The timing of the peak vertical force relative to seat-off is also of interest. Millington, et al. and Vander Linden, et al. both found the peak vertical force to have occurred after seat-off as was the case in the present study and that by Cahill, et al., but differed somewhat as to how long after seat off: 12% of movement time, or 240 ms, reported by Millington, et al.; and 6% of movement time, or 86 ms, reported by Vander Linden, et al.. On the hand, Hirschfeld, et al. found the peak vertical force to have occurred some 3% of movement time (45 ms) *before* seat-off. Why does this result differ from those of Millington, et al. and Vander Linden, et al.? One possibility has to do with the definition of seat-off: Neither Millington, et al. or Vander Linden, et al. measured the actual moment at which the buttocks lost contact with the seat, but used other methods to estimate the moment of seat-off. Thus Hirschfeld, et al. would likely argue (see below in the discussion of the location of the center of gravity relative to the center of pressure at the moment of seat-off) that in the aforementioned studies the actual seat-off occurred later than that reported, and thus the time to peak vertical GRFF would occur close to or after the actual seat-off. On the other hand, in the current study the actual moment that the buttocks lost contact with the seat was measured via the force plate on the seat, and yet the time to peak vertical GRFF still occurred after seat-off. It is not clear, then, whether the result of Hirschfeld, et al. is simply an anomaly or whether the timing of the peak vertical GRFF occurs closer and closer to seat-off with increasing age, to the point that in adulthood the peak vertical GRFF may occur at, or even before, seat-off.

*Location of the Center of Gravity Relative to the Center of Pressure at Seat-off*

There is some debate in the literature as to the location of the body's center of gravity relative to the center of pressure at the feet at the time of seat-off (i.e., the point when double support-the buttocks and feet-shifts to single support-the feet alone). The significance of the relative location of the center of gravity has to do with the degree of stability of the STS performer and the strategies that underlie the movement pattern of the upper body in the STS. As discussed in the Review of Literature, two primary strategies have been suggested (Berger, et al., 1988; Hughes, et al., 1994; Schenkman, et al. 1990): (1) "momentum transfer," in which hip and trunk flexion are used to generate momentum which can then be transferred to the whole body, and (2) "stabilization," in which trunk flexion is not used to generate momentum, but rather to position the center of gravity of the body closer to the base of support at the time of seat-off. In the momentum transfer strategy the center of gravity would be expected to lag behind the center of pressure, and the body would be expected to have appreciable forward velocity, at the time of seat-off. In the stabilization strategy, on the other hand, the center of gravity would be expected to be over the base of support and close to the center of pressure at the time of seat-off. In addition, the forward velocity of the body would be expected to be approaching zero at seat-off. As noted, these two strategies are not mutually exclusive: forward flexion might act both to move the center of gravity closer to the base of support under the feet as well as generate momentum, but even in this case the center of gravity would still be expected to lag behind (Riley, et al., 1991).

Riley, et al. (1991), preceded by Schenkman, et al. (1990), found that at the time of seat-off the center of gravity was located approximately 7 cm behind the center of pressure. Thus at the time of seat-off the subjects were in an inherently unstable position. In addition, they found that the horizontal velocity of the upper body actually reached its peak at seat-off. These results led Riley, et al. to conclude that the subjects used the upper body to generate forward momentum, as well as possibly to position the center of gravity more favorably at seat-off. However, Hirschfeld, et al. (1996) found the center of gravity to be over the center of pressure at seat-off and therefore argue that the stabilization strategy stated above is being used and that the body is in a state of stable equilibrium at the time of seat-off. They suggest that the results obtained by Riley, et al. and Schenkman, et al. are due to the fact that these authors define seat-off as the point at which the vertical reaction force at the feet begins to increase (as opposed to noting the actual point of the buttocks leaving the seat), an event that occurred about 250 ms before seat-off in the study by Hirschfeld, et al. (and about 175 ms before seat-off in the present study). Thus Hirschfeld, et al. argued that if one adjusts Riley, et al. and Schenkman, et al.'s results accordingly, the center of gravity is located over the center of pressure at seat-off. This may be true in the case of Riley, et al. and Schenkman, et al., but it ignores other studies that did define seat-off as the moment the buttocks left the seat and yet found the center of gravity to be located posterior to the center of pressure at seat-off: e.g., Kelley, et al. (1976); Murray, et al. (1967); Pai, Naughton, et al. (1994). In the present study the center of gravity was also located, on average, posterior to the center of pressure at the moment of seat-off (about 5 cm). What Hirschfeld, et al. failed to consider is that both strategies, or a combination of them, may be viable, as evidenced in the study by Hughes, et al. (1994). In other words, for what ever reason the subjects in the study by Hirschfeld, et al. may have been using the stabilization strategy, whereas in studies in which the center of gravity was found to lag behind the center of pressure at the moment of seat-off the momentum transfer strategy or a combination of the two strategies may have been used.

### *Joint Moments*

Another variable of interest is the peak joint (extension) moment experienced at the hip and knee joint during the execution of the STS movement.[3] Kotake, et al. (1993) calculated the theoretical minimum moments required for adults to execute the STS movement, and found the minimum hip and knee joint moments required to be 12.1±1.7 and 15.6±1.7, respectively. However, the study by Doorensbosch, et al. (1994) and the present study have found actual peak hip and knee joint moments that are less than the

[3] In the discussion which follows it is important to recall that the joint moments have been normalized by dividing by the subject's body weight in newtons, multiplying by the subject's height in meters, and multiplying by 100.

minimum theoretical values calculated by Kotake, et al. (see Table 9). The reason for these discrepancies is not clear, although it may relate to the model used by Kotake, et al. and its possible lack of relevance to children. Nevertheless, it is clear that the subjects in the present study had no difficulty in completing the STS movement despite comparatively low peak joint moments.

The magnitude of the mean peak hip and knee joint moments reported in the literature varies greatly, ranging from 10.8 to 39.8 for the normalized peak hip joint moment and 14.4 to 47.0 for the normalized peak knee joint moment (see Table 9). In the present study a great deal of variation existed as well, with the mean normalized peak moments for each subject ranging from 5.8 to 50.6 for the hip joint and 2.8 to 18.8 for the knee joint (see Table C5). Whereas the peak hip joint moments in the present study were similar in magnitude to those reported in the literature (although the Group 1 and 2 subjects tended to be at the lower end of the range), the peak knee joint moments tended to be lower than the values reported in the literature. This result is somewhat unexpected, as the peak ground reaction forces at the feet and the peak knee extension velocities for the subjects in the present study were greater, on the whole, than those reported in the literature (see Tables 12 and 14). On the other hand, the peak velocity of the center of gravity of the subjects in the present study tended to be lower than that reported in the literature (see Table 8). It may well be that one or more of the variables that determines the joint moment (e.g., segmental linear acceleration, angular acceleration) were lower for the subjects in the present study compared to those reported in the literature. Another possibility is related to body proportions: Compared to adults, children tend to have proportionally longer torsos and shorter legs (Malina & Bouchard, 1991), which could mean that in rotating about the knee children have a relatively smaller moment of inertia (I) and therefore a smaller moment (since $M = I\alpha$). A third possibility is that for children weight may have a greater impact than height, so that normalizing by dividing by body weight and multiplying by height results in a smaller relative moment for the children compared to the adults (of course this would apply to the hip joint moment as well).

The magnitude of the peak hip joint moment relative to the magnitude of the peak knee joint moment also differed in the present study compared to many previous studies. Namely, in nearly every case in the present study the peak hip joint moment was greater than that of the knee joint, whereas many studies (Doorenbosch, et al., 1994; Ikeda, et al., 1991; Pai & Rogers, 1991; Roebroeck, et al., 1994) found the peak knee joint moment to be the greater of the two (see Table 9). The only exception was the study by Shepherd and Gentile (1994), who found the peak hip joint moment to be about twice that of the peak knee joint moment. However, as discussed in the Review of Literature, many of the studies involving subjects with movement limitations (e.g., older adults and obese individuals) employed strategies (the stabilization and "combined" strategies; Hughes, et al., 1994) that involved less hip flexion and a smaller hip moment, but a greater knee moment. It may be that the subjects in some of the previously-mentioned studies employed a more combined type strategy. The subjects in the present study, however, seemed to use the "momentum transfer strategy" (Hughes, et al.) as evidenced by the relatively large amount of hip flexion and relatively high hip flexion velocity (see Tables 11 and 12), and by the greater magnitude of the peak hip joint moment versus the knee joint moment that they experienced.

*Strategies Used by Children in Performing the Sit-to-Stand Movement*

As noted in the Review of Literature, Cahill, et al. (1999) suggested that the increasing hip flexion and peak hip flexion velocity with increasing age seen in their subjects is due to the gradual development of greater postural and motor control. This could possibly mean that the younger children, who have less postural control and balance, employ more of a stabilization strategy and the older children, who have greater postural control and balance, use more of a momentum transfer strategy (Hughes, et al., 1994; McMillan, 1998). Unfortunately, Cahill, et al. did not measure (or at least did not report) moments about the hip and knee joints or the location of the center of gravity relative to the center of pressure at seat-off. Both of these variables are additional factors as to whether a stabilization or momentum transfer strategy (or a combination) is being used (Hughes, et al.). In the present study, however, these variables were measured, in addition to the amount of hip flexion and the peak hip flexion velocity.

If the subjects in the present study are taken as a whole and compared to results for younger adults as reported in the literature, the following may be noted: the children in the present study had shorter movement times, comparable ranges of motion at the hip joint, and comparable or greater hip flexion velocities than younger adults. Furthermore, the subjects in the present study had greater hip joint moments than knee joint moments and the center of gravity was located behind the center of pressure at seat-off. These results, together with the fact that the momentum profile of the center of gravity was similar to that reported by Riley, et al. (1991) for adults (see Figure 11), would tend to suggest that, as a whole, the children in the present study favor a momentum transfer strategy, or at the very least, a combination of the two strategies (Hughes, et al., 1994).

Comparing the above-named variables between the age groups in the present study, the following may be noted: Groups 1 and 3 had similar movement times, but Group 2 had faster movement times than the other groups; Groups 1 and 2 had similar ranges of motion at the hip, but Group 3 had a greater range of motion at the hip than the other groups; peak hip flexion velocity tended to increase with increasing age; peak hip and knee joint moments tended to increase with increasing age, but the peak hip joint moment was consistently greater than the knee joint moment; and the center of gravity was consistently located behind the center of pressure at seat-off.[4] These results show no clear developmental trend from a stabilization strategy to a momentum transfer strategy with increasing age. This is opposed to McMillan (1998) who found that at the younger ages children typically had a forward-up movement pattern (similar to the stabilization strategy), while the majority of the children had switched to a diagonal-up movement pattern (similar to the momentum transfer strategy) by 24 months of age. However, it is possible that the younger children in the present study used more of a combined strategy versus the strict momentum transfer strategy used by the older children. This is suggested by the fact that the peak hip flexion velocities of the youngest children were slightly lower than the values reported in the literature (which would be characteristic of the stabilization strategy) yet their center of gravity tended to be located behind the center of pressure at seat-off (which would be characteristic of the momentum transfer strategy), and by the fact that hip range of motion and peak hip flexion velocity increased with

[4] Out of the 120 trials performed by all of the subjects, only 18 (15%) had the center of gravity located at or in front of the center of pressure at the time of seat-off. Of these 18 "positive" trials, 8 were distributed among 4 of the 5 subjects in Group 1, 6 were distributed among 2 of the 3 subjects in Group 2, and 4 were distributed among 2 of the 4 subjects in Group 3. Thus there was no clear age trend.

increasing age. It should be kept in mind that the stabilization and momentum transfer strategies likely represent two ends of a continuum, and that a combined strategy could fall anywhere between the two (Hughes, et al., 1994). Thus the younger children are using a combined strategy which likely becomes more and more "momentum-transfer-like" with increasing age.

## SUMMARY AND RECOMMENDATIONS

The specific aims of the present study were firstly to assess as broadly as possible the kinematics and kinetics of the sit-to-stand movement in young children (especially as it compares to younger adults), and secondly to compare the biomechanics of the sit-to-stand movement among children of different ages in order to determine if any age-related differences might exist. In order to achieve the first aim, the following kinematic and kinetic variables were investigated: movement and phase times (Figure 5 and Table C1); the pattern of joint angular motion during the movement (Figure 6); ranges of motion at the hip, knee, and ankle joints (Figure 7 and Table C2); peak hip flexion angle and the time to reach this peak (Figure 8 and Table C2); peak hip flexion, hip extension, and knee extension velocities and the time at which each of these peaks occurred (Figure 9 and Table C3); the peak horizontal and vertical velocities of the center of gravity and the time at which each of these peaks occurred (Figure 10 and Table C4); the pattern of the horizontal and vertical velocities of the center of gravity during the movement (Figure 11); the kinetic energy pattern of the center of gravity during the movement (Figure 16); the pattern of the anterior-posterior and vertical ground reaction forces at the buttocks and at the feet during the movement (Figure 12); the peak vertical ground reaction force at the feet and the time at which this peak occurred (Figure 13 and Table C5); the peak hip and knee joint moments (Figure 14 and Table C5); and the location of the center of gravity relative to the center of pressure at the time of seat-off.

The results of this study indicate that the overall pattern of the STS movement is well-developed even in the youngest children and is similar to that seen in adults. These similarities include the overall joint motion pattern and the pattern of forces at the buttocks and the feet. As far as the overall joint motion is concerned, the STS movement begins with hip flexion and ankle dorsiflexion which continues until after seat-off, when flexion changes to extension, and hip and knee extension and ankle plantar flexion occur. Concerning the forces at the buttocks and feet, the STS movement is initiated by a posteriorly-directed, propulsive horizontal force from the buttocks followed shortly by a (relatively-small) posteriorly-directed force from the feet. At about the same time as the posterior force from the feet is initiated, there begins a period of loading (vertical force) at the buttocks and unloading (vertical force) at the feet. This is followed by loading at the feet which generates the propulsive vertical force for extension of the body, and the onset of an anteriorly-directed, braking horizontal force from the feet which acts to check the forward momentum of the body.

Although the overall pattern of the STS movement is similar for children in the present study to that reported for adults, differences did exist for some variables. First, the children had faster movement times than those reported in the literature for adults. It was hypothesized that this could be due to the adults performing the STS task in a more self-conscious, and therefore slower, way, or to the children rising as quickly as possible to move toward the comfort of their waiting parents. Another difference was that the children had a greater range of motion at the ankle than the adults, which, it was suggested, could be a result of increased postural sway due to a lack of postural control. A third difference was that the peak hip flexion velocities of the children tended to be greater than those reported for adults, and is perhaps related to the faster movement times of the children. Fourth, the peak vertical and horizontal velocities of the center of gravity were lower for the children compared to those reported for adults, and these velocities tended to occur later for the children. These results may also be related to a lack of postural control on the part of the children, which causes them to take longer to reach peak velocity and to attain a lower peak velocity. A fifth difference was that the normalized peak vertical ground reaction force from the feet was substantially higher for the children compared to those reported in the literature for adults, and it tended to occur later for the children. The reason for the greater peak force seen in the children is not entirely clear, but it was proposed that the faster movement times of the children might be a contributing factor. The longer time taken to reach the peak vertical force seen in the children could possibly be due to the lack of postural control cited earlier. Finally, the children had lower normalized peak knee joint moments than those reported for adults, which was unexpected due to the greater peak vertical ground reaction force and greater peak knee extension velocity experienced by the children, but which may be due to differences in body proportions between children and adults.

On the whole, most of the differences cited can likely be attributed to the faster movement times of the children and/or a relative lack of postural control and balance in the children compared to adults. It should be remembered, however, that even the youngest children did not employ a solely stabilization strategy (which would tend to be seen in individuals with a lack of balance and postural control), but had many elements of the momentum transfer strategy, and thus their strategy would be categorized as a combined strategy. But, as noted in the Discussion section, the strategy one uses to perform the STS task is on a continuum. Therefore it is likely that the children (especially the younger children) utilize a combined strategy because they lack some of the balance and postural control of adults, but as their balance and motor control improve they move more toward the momentum-transfer-end of the continuum. This seems to be borne out by the fact that the oldest children in the present study had the greatest range of motion at the hip and that peak hip flexion velocity tended to increase with increasing age. The same trend of increasing hip flexion and hip flexion velocity with increasing age was seen in the children in the study by Cahill, et al. (1999), and those authors reached a similar conclusion.

The results of this study point the way toward two future research areas on the STS movement in children. First, there is a good deal of research on the effects of chair design (e.g., seat height, backrest) on the mechanics of the STS movement in adults. Thus a logical avenue for future research would be to study the effects of these variables on children. Not only would this type of research benefit physical therapists and other rehabilitation specialists, but it would also help the furniture industry in designing and manufacturing chairs appropriate for children. Second, while the normative data on the STS movement in able-bodied children presented in this study will hopefully aid rehabilitation specialists in working with children with disabilities, specific research needs to be conducted on the performance of the STS movement in children with disabilities. Having a knowledge of how children with disabilities perform the STS movement compared to able-bodied children would enable physical therapists and others rehabilitation specialists to perform their work more effectively.

If the specific aims of the present study were to analyze the kinematics and kinetics of the sit-to-stand movement in young children and to determine if any age-related differences exist in the performance of this movement, the more overarching goal of this study was to provide much-needed fundamental information on the mechanics of the sit-to-stand movement in able-bodied children that would be of help to physical therapists and other rehabilitation specialists in the rehabilitation of injured children and children with disabilities. Only time will tell if this study achieves that goal.

# APPENDIX A: INFORMED CONSENT FORM

## INFORMED WRITTEN CONSENT FORM

This consent form is intended for parents/guardians whose children are involved in a study of the mechanics of the sit-to-stand movement and its development in young children which is being conducted by Eugene W. Brown and David M. Wisner of the Department of Kinesiology at Michigan State University.

The purpose of this study is to use video cameras and force platforms (special metal plates which measure the forces experienced by the body) to determine the mechanical way in which young children rise from a seated position to a standing position, and the developmental changes that occur in this movement pattern.

While your participation in this study does not guarantee any beneficial results for you and/or your child, the study will have benefits for certain segments of society. Namely, this study will provide information on standing movements in able-bodied young children, so that physicians and physical therapists will be better able to help children with disabilities and/or delayed physical development regain the ability to perform this movement and thus regain mobility, which is critical for independent living.

Your child's involvement in this study will include some or all of the following:

(1) His/her weight and height will be measured.
(2) Reflective markers may be placed on the joints of his/her body, so that they can be seen more clearly on video tape.
(3) He/she will be asked to stand up from a seated position on a bench (adjusted to the appropriate height) approximately 20 times while the movement is videotaped.
(4) He/she will be asked to perform the movement barefoot.
(5) You may be asked to model the movement for him/her and to verbally encourage him/her as he/she performs the movement.

The entire process should take approximately 60 minutes of your and your child's time.

As sitting and standing are daily activities that your child engages in, this study does not pose any unusual risk of injury or illness.

Your child's name will not be associated with any publication and/or presentation of the information collected in this study, and that only the two investigators (Eugene Brown and David Wisner) will know the names of the participants in this study. However, the information may be used (with no names associated with it) for demonstration, instruction, and/or study.

Your and your child's participation in this study is voluntary and you will not be compensated monetarily for your time. Note, however, that you and your child are free to discontinue your participation in this study at any time, no questions asked, without penalty.

If you have further questions about the study, you may contact either of the two investigators at any time:

Eugene W. Brown    David M. Wisner
353-6491    432-4073
ewbrown@msu.edu    wisnerda@msu.edu

If you have further questions about your and your child's role as a research subject, you may contact:

David E. Wright
Chair, University Committee on Research Involving Human Subjects
355-2180

I ________________________ (please print name) have read the preceding information and understand the procedures involved in this study, as well as its risks and benefits. I hereby agree to voluntarily participate, and allow my child ______________________________ (please print name) to voluntarily participate in this research study.

_____________________________________ ___________________

Signature of Parent/Guardian Date

APPENDIX B: QBASIC PROGRAM *INVDYN*

```
PROGRAM INVDYN

DECLARE SUB Invdynamics (footmass!, shnkmass!, thimass!, toex!, toey!, anklex!, ankley!, kneex!,
    kneey!, hipx!, hipy!, cmfootx!, cmfooty!, cmshnkx!, cmshnky!, cmthix!, cmthiy!, ifoot!, ishank!,
    ithigh!, ftaccx!, ftaccy!, shkaccx!, shkaccy!, thiaccx!, thiaccy!, grfvert!, grfhor!, xmom!, alphaft!,
    alphashk!, alphathi!, fankx!, fanky!, ankmom!, fkneex!, fkneey!, kneemom!, fhipx!, fhipy!, hipmom!)
DECLARE SUB Accel (toeaccx!, toeaccy!, ankaccx!, ankaccy!, kneeaccx!, kneeaccy!, hipaccx!, hipaccy!,
    ftaccx!, ftaccy!, shkaccx!, shkaccy!, thiaccx!, thiaccy!)
DECLARE SUB MomIn (footmass!, shnkmass!, thimass!, footlen!, shnklen!, thilen!, ifoot!, ishank!, ithigh!)
DECLARE SUB SegLen (toex!, toey!, anklex!, ankley!, kneex!, kneey!, hipx!, hipy!, footlen!, shnklen!,
    thilen!)
DECLARE FUNCTION CoPx! (grfvert!, xmom!)
DECLARE SUB CoMpro (toex, toey, anklex, ankley, kneex, kneey, hipx, hipy, cmfootx, cmfooty,
    cmshnkx, cmshnky, cmthix, cmthiy)
DECLARE SUB Masspro (wt, bodymass, footmass, shnkmass, thimass)
OPEN "C:\Basic\jtforce.dat" FOR INPUT AS #1
OPEN "C:\Basic\invdyn.txt" FOR OUTPUT AS #2

CLS
first = 0
oldid = 0
oldtrial$ = "0"
DO UNTIL EOF(1)
    INPUT #1, id, trial$, time, wt, toex, toey, anklex, ankley, kneex, kneey, hipx, hipy, grfvert, grfhor,
        xmom, toeaccx, toeaccy, ankaccx, ankaccy, kneeaccx, kneeaccy, hipaccx, hipaccy, alphaft,
        alphashk, alphathi

    IF id = oldid AND trial$ = oldtrial$ THEN
        first = 0
    ELSE
        first = 1
    END IF

    IF first = 1 THEN
        PRINT #2, ""
        PRINT #2, ""
        PRINT #2, "JOINT FORCES AND MOMENTS FOR SUBJECT"; id; "TRIAL"; " "; trial$
        PRINT #2, TAB(4); "TIME"; TAB(12); "FANKX"; TAB(22); "FANKY"; TAB(32);
                "ANKMOM"; TAB(42); "FKNEEX"; TAB(52); "FKNEEY"; TAB(62); "KNEEMOM";
                TAB(72); "FHIPX"; TAB(82); "FHIPY"; TAB(92); "HIPMOM"
    END IF

    CALL Masspro(wt, bodymass, footmass, shnkmass, thimass)
    CALL CoMpro(toex, toey, anklex, ankley, kneex, kneey, hipx, hipy, cmfootx, cmfooty, cmshnkx,
        cmshnky, cmthix, cmthiy)
    CALL SegLen(toex, toey, anklex, ankley, kneex, kneey, hipx, hipy, footlen, shnklen, thilen)
    CALL MomIn(footmass, shnkmass, thimass, footlen, shnklen, thilen, ifoot, ishank, ithigh)
    CALL Accel(toeaccx, toeaccy, ankaccx, ankaccy, kneeaccx, kneeaccy, hipaccx, hipaccy, ftaccx, ftaccy,
        shkaccx, shkaccy, thiaccx, thiaccy)
    CALL Invdynamics(footmass, shnkmass, thimass, toex, toey, anklex, ankley, kneex, kneey, hipx, hipy,
        cmfootx, cmfooty, cmshnkx, cmshnky, cmthix, cmthiy, ifoot, ishank, ithigh, ftaccx, ftaccy,
        shkaccx, shkaccy, thiaccx, thiaccy, grfvert, grfhor, xmom, alphaft, alphashk, alphathi, fankx, fanky,
        ankmom, fkneex, fkneey, kneemom, fhipx, fhipy, hipmom)
```

```
    PRINT #2, USING "####.###"; time; TAB(10); fankx; TAB(20); fanky; TAB(30); ankmom;
        TAB(40); fkneex; TAB(50); fkneey; TAB(60); kneemom; TAB(70); fhipx; TAB(80); fhipy;
        TAB(90); hipmom

    oldid = id
    oldtrial$ = trial$
LOOP

PRINT "End of File Reached"
CLOSE #1
CLOSE #2
END

SUB Masspro (wt, bodymass, footmass, shnkmass, thimass)
bodymass = wt / 9.81
footmass = .0145 * bodymass
shnkmass = .0465 * bodymass
thimass = .1 * bodymass
END SUB

SUB CoMpro (toex, toey, anklex, ankley, kneex, kneey, hipx, hipy, cmfootx, cmfooty, cmshnkx,
    cmshnky, cmthix, cmthiy)
cmfootx = .5 * (toex - anklex) + anklex
cmfooty = .5 * (ankley - toey) + toey
cmshnkx = .433 * (anklex - kneex) + kneex
cmshnky = kneey - .433 * (kneey - ankley)
cmthix = .433 * (kneex - hipx) + hipx
cmthiy = hipy - .433 * (hipy - kneey)
END SUB


SUB SegLen (toex, toey, anklex, ankley, kneex, kneey, hipx, hipy, footlen, shnklen, thilen)
footlen = SQR((anklex - toex) ^ 2 + (ankley - toey) ^ 2)
shnklen = SQR((kneex - anklex) ^ 2 + (kneey - ankley) ^ 2)
thilen = SQR((hipx - kneex) ^ 2 + (hipy - kneey) ^ 2)
END SUB

SUB MomIn (footmass, shnkmass, thimass, footlen, shnklen, thilen, ifoot, ishank, ithigh)
ifoot = footmass * (footlen / 100 * .475) ^ 2
ishank = shnkmass * (shnklen / 100 * .302) ^ 2
ithigh = thimass * (thilen / 100 * .323) ^ 2
END SUB

SUB Accel (toeaccx, toeaccy, ankaccx, ankaccy, kneeaccx, kneeaccy, hipaccx, hipaccy, ftaccx, ftaccy,
    shkaccx, shkaccy, thiaccx, thiaccy)
ftaccx = .5 * (toeaccx - ankaccx) + ankaccx
ftaccy = .5 * (ankaccy - toeaccy) + ankaccy
shkaccx = .433 * (ankaccx - kneeaccx) + kneeaccx
shkaccy = kneeaccy - .433 * (kneeaccy - ankaccy)
thiaccx = .433 * (kneeaccx - hipaccx) + hipaccx
thiaccy = hipaccy - .433 * (hipaccy - kneeaccy)
END SUB
```

```
FUNCTION CoPx (grfvert, xmom)
cpfp = -xmom / grfvert
cpcoord = .625 - cpfp
CoPx = cpcoord * 100
END FUNCTION

SUB Invdynamics (footmass, shnkmass, thimass, toex, toey, anklex, ankley, kneex, kneey, hipx, hipy,
    cmfootx, cmfooty, cmshnkx, cmshnky, cmthix, cmthiy, ifoot, ishank, ithigh, ftaccx, ftaccy, shkaccx,
    shkaccy, thiaccx, thiaccy, grfvert, grfhor, xmom, alphaft, alphashk, alphathi, fankx, fanky, ankmom,
    fkneex, fkneey, kneemom, fhipx, fhipy, hipmom)
pi = 3.1415927#
fankx = footmass * ftaccx / 100 + grfhor
fanky = footmass * 9.81 + footmass * ftaccy / 100 - grfvert
ankmom = ifoot * (alphaft * pi / 180) + fankx * ((ankley - cmfooty) / 100) + fanky * ((cmfootx - anklex) /
    100) + grfvert * ((cmfootx - CoPx(grfvert, xmom)) / 100) - grfhor * cmfooty / 100
fkneex = shnkmass * shkaccx / 100 - fankx
fkneey = shnkmass * shaccy / 100 - fanky
kneemom = ishank * (alphashk * pi / 180) - ankmom + fkneex * ((kneey - cmshnky) / 100) + fkneey *
    ((cmshnkx - kneex) / 100) - fankx * ((cmshnky - ankley) / 100) - fanky * ((anklex - cmshnkx) / 100)
fhipx = thimass * thiaccx / 100 - fkneex
fhipy = thimass * thiaccy / 100 - fkneey
hipmom = ithigh * (alphathi * pi / 180) - kneemom + fhipx * ((hipy - cmthiy) / 100) + fhipy * ((cmthix -
hipx) / 100) - fkneex * ((cmthiy - kneey) / 100) - fkneey * ((kneex - cmthix) / 100)
END SUB
```

# APPENDIX C: MEAN DATA FOR ALL SUBJECTS

**Table C1.** Mean (± s.d.) movement times across ten trials for each subject, including time in seconds for Phases 1, 2, and 3 (t1, t2, and t3, respectively); time for Phases 1, 2, and 3 as a percentage of total movement time (Phase 1 %, Phase 2 %, and Phase 3%, respectively) and total movement time in seconds (t total).

| Age Group | Subject | t1 | Phase 1 % | t2 | Phase 2 % | t3 | Phase 3 % | t total |
|---|---|---|---|---|---|---|---|---|
| 1 (12-18 mo.) | 5 | 0.6 (±0.2) | 66 (± 7) | 0.2 (±0.1) | 24 (±17) | 0.1 (±0.1) | 10 (±16) | 0.8 (±0.2) |
| | 8 | 0.8 (±0.3) | 52 (±15) | 0.2 (±0.1) | 14 (± 6) | 0.5 (±0.4) | 34 (±20) | 1.5 (±0.4) |
| | 10 | 0.8 (±0.2) | 53 (± 5) | 0.2 (±0.2) | 16 (±12) | 0.5 (±0.2) | 31 (±14) | 1.5 (±0.2) |
| | 11 | 0.5 (±0.1) | 57 (± 9) | 0.2 (±0.1) | 20 (±13) | 0.2 (±0.1) | 23 (±15) | 0.9 (±0.1) |
| | 12 | 0.7 (±0.1) | 48 (± 8) | 0.3 (±0.1) | 24 (± 9) | 0.4 (±0.2) | 28 (±12) | 1.4 (±0.2) |
| Group Mean | | 0.7 (±0.2) | 55 (±11) | 0.2 (±0.1) | 20 (±12) | 0.3 (±0.3) | 25 (±17) | 1.2 (±0.4) |
| 2 (24-36 mo.) | 2 | 0.5 (±0.2) | 52 (±11) | 0.1 (±0.1) | 12 (± 7) | 0.3 (±0.1) | 36 (±14) | 1.0 (±0.2) |
| | 3 | 0.5 (±0.1) | 56 (±10) | 0.1 (±0.1) | 12 (± 6) | 0.3 (±0.1) | 33 (±12) | 0.9 (±0.2) |
| | 7 | 0.5 (±0.1) | 61 (± 5) | 0.1 (±0.1) | 17 (±17) | 0.2 (±0.2) | 23 (±18) | 0.8 (±0.2) |
| Group Mean | | 0.5 (±0.1) | 56 (± 9) | 0.1 (±0.1) | 13 (±11)* | 0.3 (±0.2) | 30 (±16) | 0.9 (±0.2)* |
| 3 (48-60 mo.) | 1 | 0.5 (±0.1) | 50 (± 9) | 0.2 (±0.1) | 18 (± 9) | 0.4 (±0.3) | 33 (±13) | 1.0 (±0.2) |
| | 4 | 0.6 (±0.1) | 43 (±10) | 0.1 (±0.1) | 6 (± 4) | 0.7 (±0.4) | 51 (±11) | 1.4 (±0.4) |
| | 6 | 0.5 (±0.1) | 47 (± 5) | 0.2 (±0.1) | 15 (± 8) | 0.5 (±0.2) | 38 (±10) | 1.2 (±0.3) |
| | 9 | 0.6 (±0.1) | 54 (± 8) | 0.2 (±0.1) | 17 (± 9) | 0.3 (±0.2) | 29 (±16) | 1.0 (±0.2) |
| Group Mean | | 0.5 (±0.1) | 49 (± 9)*† | 0.2 (±0.1) | 14 (± 9)* | 0.5 (±0.3) | 38 (±15)* | 1.2 (±0.3)† |
| Grand Mean | | 0.6 (±0.2) | 53 (±10) | 0.2 (±0.1) | 16 (±11) | 0.4 (±0.3) | 31 (±17) | 1.1 (±0.4) |

* Significantly different from Group 1, $p < .05$
† Significantly different from Group 2, $p < .05$

**Table C2.** Mean (± s.d.) joint range of motion, peak hip flexion angle, and time to peak hip flexion (expressed as a percentage of total movement time), across ten trials for each subject.

| Age Group | Subject | Ankle ROM (°) | Knee ROM (°) | Hip ROM (°) | Peak Hip Flexion (°) | Time to Peak (%) |
|---|---|---|---|---|---|---|
| 1 (12-18 mo.) | 5 | 31 (±13) | 57 (± 6) | 84 (±13) | 103 (± 7) | 46 (±15) |
| | 8 | 33 (±16) | 58 (±31) | 103 (±17) | 123 (±13) | 39 (±10) |
| | 10 | 32 (± 7) | 59 (±15) | 101 (±13) | 117 (± 7) | 38 (± 7) |
| | 11 | 27 (±11) | 64 (± 9) | 76 (±15) | 101 (±13) | 34 (±12) |
| | 12 | 21 (±10) | 65 (±10) | 87 (±10) | 107 (± 6) | 30 (±11) |
| Group Mean | | 29 (±12) | 61 (±16) | 90 (±17) | 110 (±13) | 38 (±12) |
| 2 (24-36 mo.) | 2 | 22 (± 7) | 68 (±13) | 93 (±14) | 106 (± 7) | 37 (± 8) |
| | 3 | 28 (±11) | 56 (±16) | 79 (±12) | 92 (±11) | 45 (±10) |
| | 7 | 27 (± 7) | 57 (±13) | 87 (±14) | 112 (± 8) | 47 (± 4) |
| Group Mean | | 25 (± 9) | 60 (±15) | 86 (±14) | 103 (±12) | 43 (± 8)* |
| 3 (48-60 mo.) | 1 | 41 (±16) | 79 (± 9) | 107 (±13) | 132 (± 7) | 43 (± 7) |
| | 4 | 30 (±10) | 107 (± 5) | 120 (± 9) | 121 (± 7) | 37 (± 9) |
| | 6 | 36 (± 8) | 84 (±11) | 127 (±10) | 134 (± 5) | 39 (± 2) |
| | 9 | 31 (±19) | 61 (±27) | 99 (±16) | 122 (± 9) | 41 (± 6) |
| Group Mean | | 35 (±14)*† | 83 (±22)*† | 113 (±16)*† | 127 (± 9)*† | 40 (± 6) |
| Grand Mean | | 30 (±13) | 69 (±21) | 97 (±20) | 114 (±15) | 40 (±10) |

* Significantly different from Group 1, $p < .05$
† Significantly different from Group 2, $p < .05$

**Table C3.** Mean (± s.d.) peak hip flexion velocity, hip extension velocity, and knee extension velocity; and time to peak hip flexion (thfv), hip extension (thev), and knee extension (tkev)velocities (expressed as a percentage of total movement time), across ten trials for each subject.

| Age Group | Subject | Pk. Hip Flex. V (°/s) | Pk. Hip Ext. V (°/s) | Pk. Knee Ext. V (°/s) | thfv (%) | thev (%) | tkev (%) |
|---|---|---|---|---|---|---|---|
| 1 (12-18 mo.) | 5 | 49 (±15) | 267 (± 58) | 193 (±42) | 17 (±15) | 79 (± 7) | 76 (±11) |
| | 8 | 81 (±28) | 180 (± 43) | 117 (±24) | 17 (±15) | 75 (±17) | 68 (±20) |
| | 10 | 75 (±24) | 179 (± 33) | 108 (±22) | 22 (±10) | 73 (±14) | 81 (±14) |
| | 11 | 64 (±21) | 241 (± 93) | 205 (±74) | 17 (±14) | 76 (± 9) | 76 (±10) |
| | 12 | 53 (±14) | 163 (± 33) | 99 (±36) | 17 (±11) | 74 (± 8) | 72 (±10) |
| Group Mean | | 64 (±24) | 206 (± 68) | 143 (±62) | 18 (±12) | 75 (±11) | 74 (±14) |
| 2 (24-36 mo.) | 2 | 80 (±24) | 271 (± 81) | 236 (±83) | 22 (± 8) | 67 (±12) | 67 (±13) |
| | 3 | 86 (±29) | 295 (± 92) | 211 (±80) | 27 (±11) | 70 (±13) | 70 (±12) |
| | 7 | 100 (±19) | 268 (± 61) | 175 (±43) | 29 (± 8) | 81 (± 5) | 80 (± 8) |
| Group Mean | | 89 (±25)* | 278 (± 77)* | 208 (±73)* | 26 (± 9)* | 72 (±12) | 72 (±12) |
| 3 (48-60 mo.) | 1 | 139 (±43) | 297 (±116) | 215 (±62) | 25 (± 7) | 81 (±11) | 73 (±16) |
| | 4 | 59 (±30) | 229 (± 53) | 220 (±64) | 26 (± 6) | 73 (±15) | 74 (±14) |
| | 6 | 124 (±37) | 269 (± 62) | 204 (±67) | 26 (± 4) | 76 (±10) | 80 (± 8) |
| | 9 | 99 (±32) | 260 (± 79) | 185 (±98) | 25 (± 7) | 74 (± 8) | 82 (±10) |
| Group Mean | | 105 (±46)* | 264 (± 82)* | 206 (±73)* | 25 (± 6)* | 76 (±11) | 77 (±13) |
| Grand Mean | | 84 (±37) | 243 (± 81) | 180 (±75) | 23 (±10) | 75 (±11) | 75 (±13) |

* Significantly different from Group 1, $p < .05$

**Table C4.** Mean (± s.d.) horizontal and vertical components of the peak velocity of the whole body center of gravity, as well as the time to peak horizontal (tcghor) and vertical (tcgvert) velocities of the center of gravity (expressed as a percentage of total movement time), across ten trials for each subject.

| Age Group | Subject | CG Velocity, hor. (cm/s) | CG Velocity, vert. (cm/s) | tcghor (%) | tcgvert (%) |
|---|---|---|---|---|---|
| 1 (12-18 mo.) | 5 | 44.2 (±17.7) | 23.2 (± 8.9) | 96 (±16) | 86 (±12) |
| | 8 | 21.2 (± 8.0) | 20.3 (± 9.3) | 46 (±21) | 64 (±16) |
| | 10 | 16.0 (± 3.4) | 15.3 (± 2.9) | 52 (±10) | 61 (± 6) |
| | 11 | 17.4 (± 8.0) | 22.8 (± 7.0) | 56 (±25) | 68 (±12) |
| | 12 | 14.0 (± 3.6) | 15.4 (± 3.4) | 39 (±13) | 60 (±11) |
| Group Mean | | 22.5 (±14.5) | 19.4 (± 7.5) | 58 (±27) | 68 (±15) |
| 2 (24-36 mo.) | 2 | 27.1 (± 4.9) | 34.7 (± 9.7) | 46 (±14) | 64 (±13) |
| | 3 | 37.0 (±14.9) | 32.6 (± 6.2) | 62 (±20) | 70 (±16) |
| | 7 | 37.6 (± 6.7) | 32.8 (± 7.2) | 59 (±15) | 78 (± 7) |
| Group Mean | | 33.9 (±10.7)* | 33.4 (± 7.6)* | 56 (±17) | 71 (±13) |
| 3 (48-60 mo.) | 1 | 45.0 (±15.7) | 38.0 (±20.2) | 41 (± 8) | 74 (±19) |
| | 4 | 21.0 (± 8.7) | 37.8 (± 9.1) | 32 (±21) | 58 (±14) |
| | 6 | 49.2 (±10.0) | 40.3 (± 7.4) | 37 (± 5) | 63 (±10) |
| | 9 | 32.8 (± 6.1) | 31.8 (±15.8) | 48 (±12) | 67 (±10) |
| Group Mean | | 37.0 (±15.2)* | 37.0 (±13.9)* | 40 (±14)*† | 65 (±14) |
| Grand Mean | | 30.2 (±15.3) | 28.8 (±12.9) | 51 (±22) | 68 (±14) |

* Significantly different from Group 1, $p < .05$
† Significantly different from Group 2, $p < .05$

**Table C5.** Mean (± s.d.) peak vertical ground reaction force at the feet (GRFF) normalized per body weight, time to peak vertical GRFF (expressed as a percentage of total movement time), peak normalized hip moment, and peak normalized knee moment across ten trials for each subject. The moments were normalized by dividing by weight (N), multiplying by height (m), and multiplying by 100.

| Age Group | Subject | Peak GRFF (% BW) | Time to Peak GRFF (%) | Peak Hip Moment | Peak Knee Moment |
|---|---|---|---|---|---|
| 1 (12-18 mo.) | 5 | 149 (±47) | 87 (±27) | 15.0 (± 7.6) | 8.0 (±6.0) |
| | 8 | 126 (±29) | 63 (±20) | 11.8 (± 8.0) | 9.2 (±7.0) |
| | 10 | 142 (±26) | 67 (±19) | 6.8 (± 5.8) | 7.6 (±7.4) |
| | 11 | 142 (±25) | 62 (±12) | 5.8 (± 1.4) | 2.8 (±0.4) |
| | 12 | 126 (±25) | 53 (±11) | 5.8 (± 1.8) | 3.4 (±1.0) |
| Group Mean | | 137 (±31) | 66 (±21) | 9.0 (± 6.6) | 6.2 (±5.8) |
| 2 (24-36 mo.) | 2 | 129 (±16) | 59 (±16) | 11.2 (± 2.2) | 6.2 (±2.0) |
| | 3 | 195 (±67) | 64 (±24) | 17.8 (± 9.2) | 14.0 (±6.4) |
| | 7 | 164 (±26) | 76 (±26) | 15.0 (± 4.4) | 8.0 (±5.0) |
| Group Mean | | 163 (±49)* | 67 (±23) | 14.6 (± 6.4)* | 9.4 (±5.8)* |
| 3 (48-60 mo.) | 1 | 134 (±16) | 49 (±16) | 26.8 (± 7.8) | 12.4 (±4.8) |
| | 4 | 139 (±15) | 49 (±14) | 24.8 (± 6.6) | 12.8 (±2.4) |
| | 6 | 211 (±26) | 52 (± 6) | 50.6 (± 8.0) | 18.8 (±5.4) |
| | 9 | 136 (±18) | 62 (± 9) | 22.2 (± 9.6) | 17.0 (±6.0) |
| Group Mean | | 155 (±38) | 53 (±13)*† | 31.0 (±13.4)*† | 15.2 (±5.4)*† |
| Grand Mean | | 150 (±40) | 62 (±20) | 17.8 (±13.6) | 10.0 (±6.8) |

* Significantly different from Group 1, $p < .05$
† Significantly different from Group 2, $p < .05$

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