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**Trunk posture and motion**

The trunk functions to provide support for the head and a mobile platform on which the upper and lower limbs may move. Daily activities require static trunk postures such as those in sitting or standing and the ability to change positions that may require the trunk to be mobile. In addition the trunk may be used to position the limbs such as during trunk forward flexion in order to pick something up from the floor or trunk rotation to the side to allow increased vision.

**Trunk posture in standing and sitting**

In the standing posture the vertebral column is curved, with the cervical and lumbar spine convex to the anterior (lordosis) and the thoracic spine concave to the anterior (kyphosis). The pelvis is anteriorly tilted such that the anterior superior iliac spine is vertically above the anterior inferior iliac spine and the sacral end plate is inclined forward (Andersson et al 1979, Chaffin and Andersson 1991). These curvatures effectively reduce the energy requirements of standing (Bridger 1995). It has been suggested that to maintain an upright posture as the pelvis rotates that the size of the lordotic curvature must change (Chaffin and Andersson 1991). In standing, the correlation between the inclination of the sacral base and the lumbar lordosis is good, although correlation between thoracic kyphosis and lumbar lordosis is poor (Stagnara et al 1982). The size of the curvatures is also highly variable from subject to subject (Stagnara et al 1982). Therefore differences in posture from person to person are great and many variations of postural combinations are possible.

In sitting, the pelvis rotates posteriorly, the sacral end plate is more horizontal and the lumbar lordosis decreases (Andersson et al 1979, Chaffin and Andersson 1991, Riley and Bader 1988). As in standing, it appears that there are large inter subject differences in

Trial to trial and day to day stability of lumbar and thoracic curvatures and pelvic inclination measurements in nonpregnant females while standing have been reported as high (Bullock et al 1987, Bullock-Saxton 1993, Chaipackdee et al 1993, Hart and Rose 1986, Walker et al 1987). Bullock-Saxton (1993) also reported that the spinal curvatures and pelvic inclination remained constant for at least two years. Thus females have consistent postural alignment when asked to stand in a comfortable erect posture (Bullock et al 1987, Bullock-Saxton 1993). Small differences of 2-3° between repeated tests of quiet standing were reported by Moore et al (1990) and Willner (1981) for lumbar lordosis and thoracic kyphosis.

For seated posture, significant trial to trial variation has been reported particularly for the thoracic kyphosis (Riley and Bader, 1985 cited in Riley and Bader, 1988). Black et al (1996), however, reported excellent trial to trial stability for pelvic inclination and lumbar curves while head inclination stability with retesting was fair. Differences of 2-6° in postural alignment were reported from trial to trial (Black et al 1996). The largest difference was seen for the head segment inclination while the smallest difference was seen for the lumbar curve (Black et al 1996).

The validity of using surface measurements to represent the underlying vertebral bodies is an important issue when investigating posture. When postural curve comparisons were investigated using surface measurements and radiographs, the literature reports varying results. Willner (1981) reported very high and good correlation coefficients between surface measurement and x-rays in standing for the thoracic and lordotic curves respectively. Hart and Rose (1986) also reported good correlation although Bryan et al
(1989) found very poor correlation between surface measurements and radiographs of the lumbar spine. Stokes et al (1987) reported poor correlations for the range of motion of the seated lumbar spine measured by radiographs and flexible rule. Differences of $\pm 6^\circ$ between standing lumbar spine range of motion from flexible rule and radiographs were reported by Tillotson and Burton (1990). Comparison of these studies is difficult due to differences in methodology. Differences, however, would be expected between surface measurements and radiographs as the same boney landmarks are not used, palpation and interpretation of radiograph skills may be different and intervening subcutaneous tissue between the skin and the underlying vertebrae will alter the surface shape (Bryan et al 1989, Hart and Rose 1986, Stokes et al 1987). Any variation in test to test spinal curvatures reported using surface measurements should anticipate extraneous factors such as changes in the amount of adipose tissue.

**Trunk motion during anatomical movements**

The kinematics of the lumbar, thoracic and sacral spine during stylised anatomical movements such as forward flexion, lateral flexion and axial rotation while standing or seated have been reported. The majority of these studies have investigated lumbar segment motion relative to the pelvis (Dolan and Adams 1993, Dumas et al 1998b, Esola et al 1996, Hindle et al 1990, Pearcy and Hindle 1989, Russell et al 1993a, Sykes et al 1993, Vachalathiti et al 1995). Thoracolumbar spinal motion has been reported relative to the pelvis (Gill and Callaghan 1996, Vachalathiti 1994) and thoracic spine motion relative to the adjacent segment (Lariviere et al 2000, Vachalathiti 1994, Willems et al 1996). Sacral and pelvic motion has been reported as peak inclination (Dolan and Adams 1993), and range of motion (Dumas et al 1998b, Esola et al 1996, Lariviere et al 2000).
Investigation of symmetry of right versus left lateral flexion and axial rotation is problematic due to difficulties in ascertaining the central neutral position as the subject moved from side to side (Vachalathiti 1994), and many papers report the full range of right to left motion (Dumas et al 1998b, Gill and Callaghan 1996, Hindle et al 1990, Pearcy and Hindle 1989, Russell et al 1993b). Hindle et al (1990), noted many individual variations in the symmetry of right to left side range of motion, however, paired Student-t tests showed no consistent differences for standing right to left lateral flexion and axial rotation. Where individual right and left side range of motion have been reported, although no investigation of symmetry was performed, examination of the means supports the results of (Hindle et al 1990, Vachalathiti 1994, Vachalathiti et al 1995, Willems et al 1996).

The range of motion of trunk movement may be affected by velocity. Inertial effects may mean that increased velocity causes a large angular momentum, which may cause a greater range of motion (Vachalathiti et al 1995). Vachalathiti et al (1995) reported increased range of motion for seated axial rotation as velocity increased. Seated lateral flexion range of motion decreased, however, as velocity increased which was thought to be due to difficulties with balance. The reported changes were also small and the functional significance of such small increases or decreases was questioned (Vachalathiti 1994).

Seated and standing forward flexion range of motion appears to be unaffected by changes in velocity (Marras and Wongsam 1986, Vachalathiti et al 1995). During seated forward flexion, end of range is limited by apposition of the thigh and abdomen (Vachalathiti et al 1995), however, this is not generally the case in standing. It is possible, that as with seated lateral flexion, problems with balance are the limiting factor to the effects of increased velocity on standing forward flexion.
Statistical evidence in reported literature of the stability of trunk kinematic measurements related to retesting varies greatly in the indices used to reported the stability. Although differing measures were used, the range of motion of the lumbar spine has been described as being consistent within subjects from trial to trial (Hindle et al 1990, Pearcy and Hindle 1989) or test to retest (Dolan and Adams 1993, Lariviere et al 2000, McGregor et al 1995, Sykes et al 1993). Test to test variability of the range of motion of the thoracic spine during seated movements was also thought to be very small (Willems et al 1996). The magnitude of the natural variability, however, has varied depending on the measurement devices and type of motion. Test to test stability of thoracolumbar spine range of motion during fast movements was found to be lower than preferred speed movements (Gill and Callaghan 1996). McGregor et al (1995) and Lariviere et al (2000) reported good to excellent test to test stability of lumbar spine motion during standing lateral flexion and forward flexion. Stability during axial rotation, however, was poor (McGregor et al 1995). Hindle (1992) cited in Russell et al (1992), reported day to day differences for lumbar spine motion during standing forward flexion were larger than those for axial rotation as measured by an electro-magnetic device. The variation for axial rotation, however, was larger than for lateral flexion. Variations in the range of lumbar forward flexion and lateral flexion over consecutive weekly tests were small (Dolan and Adams 1993, Lariviere et al 2000), however, the stability of trunk range of motion over time periods such as that needed to investigate motion as pregnancy proceeds is unknown.
Rising to stand from a chair

Raising the seated body from a chair is fundamental motion (Yoshida et al 1983) that is a common activity of daily living. During the motion the total body centre of mass is firstly moved forward and slightly down, then although continuing to move forward the vertical movement reverses and the total body centre of mass rises (Carr 1992, Kelley et al 1976, Pai and Rogers 1990, Riley et al 1991, Roebroek et al 1994). Initially the motion of the total body centre of mass is within limits related to the base of support provided by the seat and the feet. At the end of the motion the base of support is provided by the feet only. Motion, however, from one base of support to another must be first initiated then controlled whilst balance is maintained.

Characterisation of movement events and movement timing

Although it is usually performed in isolation, rising to stand from a chair may be thought of as cyclic in that it is essentially a similar sequence of body segment movements each time it is performed throughout the day. In order to relate kinematic, kinetic, and electromyographic parameters to an individual's rising to stand movement, the parameters may be expressed as a function of the movement cycle. The beginning and end of the cycle may be established in relation to a kinetic, kinematic or temporal-spatial event such as seat-off. Parameter data may then be divided into individual movement cycles. Cyclic activities also may be described in terms of movement phases in order to expedite movement description in a uniform manner. There appears, however, to be no consistent method used throughout the literature to describe rising to stand from a chair in terms of phases of the movement. Several authors divide the movement into two phases where a pre-extension, flexion or forward thrust phase was followed by an extension phase although the parameters used to distinguish the phases differed (Hirschfeld et al 1999, Khemlani et al
The start of movement has been defined using values related to the sagittal plane movement of the head (Rodrigues-de-Paula Goulart and Valls-Sole 1999), shoulder marker (Coghlin and McFadyen 1994), and hip joint (Gross et al 1998, Kerr et al 1997, Millington et al 1992, Rodosky et al 1989), and changes in vertical (Carr 1992, Shepherd and Gentile 1994) and anteroposterior ground reaction force under the feet (Kralj et al 1990) or buttocks (Hirschfeld et al 1999). The beginning of the extension phase has been described as when the anteroposterior ground reaction force is maximum (Kralj et al 1990), reversal of head movement and increase in knee extension (Nuzik et al 1986), peak hip and knee joint moments (Rodosky et al 1989) or indicated by a seat switch (Carr and Gentile 1994, Crosbie et al 1997, Gross et al 1998, Khemlani et al 1999, Rodrigues-de-Paula Goulart and Valls-Sole 1999). The end of the movement has been related to sagittal plane motion of the knee (Ada and Westwood 1992, Kralj et al 1990), or hip joint (Ada and Westwood 1992, Carr and Gentile 1994, Gross et al 1998), or cessation of sagittal plane motion of markers on the greater trochanter and acromion (Crosbie et al 1997).

As the parameters used to define the phases of the movement differed between studies, comparison of the timing of the movement phases is difficult. Reported total movement duration ranged from 168 - 228 ms (Coghlin and McFadyen 1994) to 178 - 421ms (Kralj et al 1990). Variability between subjects has been noted (Baer and Ashburn 1995, Coghlin and McFadyen 1994, Hirschfeld et al 1999, Jeng et al 1990, Kralj et al 1990). Variability between trials is also seen (Ada and Westwood 1992, Coghlin and McFadyen 1994, Kerr et al 1994). In general the trial to trial natural variability in timing is thought to be small (Baer and Ashburn 1995, Durward 1994, Jeng et al 1990). Kerr et al (1994) reported the
coefficient of variation of total movement duration was less than 5% for day to day reliability in one subject for a constrained chair rise.

**Kinematics**

The general pattern of body movement during sit-to-stand motion may be descriptively summarised as follows. From the upright seated posture the head, trunk and pelvis are first flexed with the femur, shank and feet stationary. Forward movement of the upper segments then continues with the knee extending and the ankle dorsiflexing. As the rest of the body continues to move forward, the head extends followed sequentially by the trunk and pelvis. The ankle moves towards plantarflexion as the trunk extends. As the movement concludes the head again may be flexed to reorientate the head to a standing posture (Nuzik et al 1986, Schenkman et al 1990). The lower limb extension onset sequence is knee, hip then ankle (Khemlani et al 1999).

The kinematics of the ankle, knee and hip joints and the thigh, pelvis and trunk segments during sit-to-stand have been investigated by several authors in order to quantify the segment movements and give insight into the principal components of the motion. The ankle remains in dorsiflexion throughout the movement (Roebroek et al 1994). The range of motion is approximately 15° (Pai and Rogers 1991b) with a maximum dorsiflexion of 20-32° (Schenkman et al 1990). Angular velocity of the ankle joint is low in comparison to the knee and hip joints (Roebroek et al 1994).

The knee joint remains at a constant angle until the body centre of mass is decelerated horizontally (Burdett et al 1985). The knee joint then extends until the end of the movement with reported range of motion varying from 75° (Rodosky et al 1989) to 97° (Jevsevar et al 1993). The knee joint angular velocity increases to 62% of the total
movement time, then decreases (Roebroek et al 1994) with the reported maximum angular velocity varying from 116°/sec (Schenkman et al 1996) to 159°/sec (Jevsevar et al 1993).

The hip joint is first flexed then extended from seat off until the end of the movement (Roebroek et al 1994) with a reported range of movement ranging from 73° (Nuzik et al 1986) to 95° (Roebroek et al 1994). Peak hip flexion velocity occurs at 22% of total movement time and peak hip extension velocity at 59% of total movement time (Roebroek et al 1994).

The kinematics of the upper limb during the sit-to-stand motion have also been investigated. When using armrests, the forearm first flexes and supinates, then extends and pronates (Packer et al 1993). When the upper limb is free to move ie no armrests, two principal strategies of upper limb use have been identified in the elderly (Millington et al 1992). The more common strategy was the use of elbow flexion, peaking in the first half of the movement and little shoulder flexion. The second strategy was the use of shoulder flexion, again peaking in the first half of the motion, while keeping the elbows relatively straight (Millington et al 1992). In young men, Carr (1991) noted that the shoulder joint first extended then flexed, with the onset of shoulder flexion being closely related to the onset of lower limb extension.

Movement of the trunk is thought to be essential for sit-to-stand, as sit-to-stand requires propulsive impulse at the beginning of movement to initiate the forward momentum (Pai and Rogers 1991b, Pai and Rogers 1990). The propulsion is thought to be generated by angular velocity of the trunk and pelvis segments in the sagittal plane (Kralj et al 1990, Riley et al 1991, Schenkman et al 1990, Shepherd 1991). Once sufficient momentum has been gained, vertical acceleration begins and seat unloading commences (Kralj et al 1990). Bridson (1993), also suggests that forward trunk flexion may be important for postural
adjustment in positioning the body centre of mass over the feet at thighs off. Few studies, however, have investigated the contribution of the trunk and pelvis as separate segments. Schenkman et al (1990) reported the trunk flexed on the pelvis for some subjects while for others the trunk and pelvis moved together. Krebs et al (1992), describe the trunk and pelvis as moving in synchrony until lift-off, however after lift-off the pelvis flexed more than the trunk. In addition, there is a paucity of research on the movement of the upper trunk relative to the lower trunk and pelvis segments and the contribution of the upper trunk to the sit-to-stand. It is known that the acromion and midiliac crests have different movement trajectories, while those of the midiliac crest and greater trochanter are similar (Nuzik et al 1986). As the movement of the trunk and pelvis are thought to be essential components of sit-to-stand, further research is warranted to elucidate the contribution of the upper and lower trunk and pelvis segments to the movement.

Kinematics of the sit-to-stand motion are affected by the initial position of the feet and trunk. Head displacement is increased when the shank is positioned at 90° to the floor (Stevens et al 1989). Khemlani et al (1999), reported that peak hip angular velocity and hip flexion displacement increased as feet moved forward from a feet back position to a feet forward position. As initial trunk position becomes more flexed the amplitudes of hip flexion and peak hip flexion velocity significantly decrease, and the relative timing of onsets of hip and knee extension alter (Shepherd and Gentile 1994).

The use of the upper limbs during sit-to-stand motion has also been found to affect the kinematics of the motion (Alexander et al 1991, Burdett et al 1985, Carr 1991). Ankle joint range of motion, maximum ankle dorsiflexion and trunk flexion have been reported to decrease with hand push (Alexander et al 1991, Burdett et al 1985). The amplitude of trunk flexion also decreases as the amplitude of arm flexion decreases (Carr and Gentile 1994).
Ankle joint displacement shows greater variation and hip and knee joints fail to fully extend at movement end when arm movement is restricted (Carr 1991).

The displacement of the trunk, knee and ankle in the sagittal plane during sit-to-stand has been reported to be stable from trial to trial with small inter trial differences and generally good stability indices (Jeng et al 1990, Jevsevar et al 1993, Krebs et al 1992). Carr and Gentile (1994) reported coefficient of variations of 19%, 13% and 31% respectively for the hip, knee and ankle indicating that the variability differs between joints. Trial to trial consistency of performance of head movements are moderate, and elbow and shoulder movements are variable across subjects (Jeng et al 1990, Millington et al 1992, Packer et al 1993). Packer et al (1993) reported small intrasubject variation but larger intersubject variation for the elbow joint. Although trial to trail variability for displacement in the sagittal plane has been established, trial to trial variability in the frontal and transverse planes appears to have not been examined.

**Kinetics**

The forces and their moments generated in relation to the rising to stand from a chair movement may be used to elucidate parameters such as the amount of muscle torque, contact forces within the joint, and the position of the total body's centre of mass. Such parameters are of interest to clinicians as this knowledge may be used to understand the dynamic mechanics of the motion.

Ground reaction forces (GRF) during the sit-to-stand motion have been investigated with both feet positioned on a single force platform (Burdett et al 1985, Carr 1992, Kralj et al 1990, Millington et al 1992, Pai and Rogers 1990), each foot on a separate force platform (Jevsevar et al 1993, Riley et al 1991, Rodosky et al 1989) or one foot only on a single force platform (Roebroek et al 1994). Force platform data has been used to report peak
GRF (Jevsevar et al 1993, Millington et al 1992) and in further calculations to determine segment moments (Burdett et al 1985, Carr 1992, Rodosky et al 1989, Roebroek et al 1994). Consistent patterns are seen in the peaks of the vertical and anterio-posterior GRF. The vertical GRF shows an initial decrease during the pre-extension phase followed by a rapid increase (Gioftsos and Grieve 1996, Hirschfeld et al 1999, Millington et al 1992, Stevens et al 1989). The initial decrease may be related to the initiation of trunk flexion by the hip flexors. Concentric muscle contraction may not only move the trunk forward but also lift the lower limb up leading to a reduction in the vertical ground reaction force. The decrease in vertical force under the feet may also be a passive force change related to the loading of the buttocks prior to forward movement of the trunk (Hirschfeld et al 1999). Following the initial decrease, the vertical ground reaction force would then increase as more weight is borne by the feet (Stevens et al 1989) and peak just after seat off (Crosbie et al 1997, Millington et al 1992). The maximum vertical GRF is approximately 1.11-1.30 times body weight (Hirschfeld et al 1999, Jevsevar et al 1993, Millington et al 1992). The anterio-posterior GRF first shows a small posterior peak then a large anterior peak (Gioftsos and Grieve 1996, Hirschfeld et al 1999, Millington et al 1992, Stevens et al 1989). The posterior peak may be related to forward propulsion of the centre of mass (Gioftsos and Grieve 1996, Millington et al 1992, Stevens et al 1989) or the passive results of transferring load posteriorly to the buttocks (Hirschfeld et al 1999). The larger anterior peak force brakes the forward movement (Gioftsos and Grieve 1996, Hirschfeld et al 1999, Millington et al 1992, Stevens et al 1989) and is thought to be maximum at thighs off (Kralj et al 1990). The mediolateral GRF is thought to show only small fluctuations from side to side with no consistent pattern of peaks (Millington et al 1992, Stevens et al 1989). Hirschfeld et al (1999), however, described an initially medially directed GRF followed by
an increasing laterally directed GRF after seat-off. The magnitude of the mediolateral GRF was small, approximately 4% of body weight.

Calculation of component moments acting on segments may be used to describe the movement of a multi-segmented system. These moments include those created by the gravitational force, those created by muscle force, and inertial moments created by the movement of the segment. Although various authors have chosen to include (Carr 1991, Crosbie et al 1997, Jevsevar et al 1993, Koh 1992, Rodosky et al 1989) or assume negligible (Bajd et al 1982, Schultz et al 1992) the segment inertia, the relative contribution of segmental inertia to the dynamics of the sit-to-stand motion have been rarely investigated. Crosbie et al (1997) reported that the percentage contribution to net absolute muscle moment after thighs off of the inertial moment of the shank, thigh and head arm trunk segments were small. It is possible, however, that although in a normal population the contribution of the inertial moment may be small, in subjects such as those of late pregnancy where the muscle contribution may have maximally plateaued, the small contribution by the inertial moment may be a significant factor in the movement success.

Rising to stand from chair is a mechanically demanding task which requires adequate moments to be developed at each joint in temporally coordinated manner (Bahrami et al 2000). The level of moment production and the temporal applications of those moments are required in order to fully describe the mechanical demands. The hip and knee joint peak extension moment occurs around seat-off and the extension moment then decreases as the subject continues to rise (Carr and Gentile 1994, Coghlin and McFadyen 1994, Gross et al 1998, Kelley et al 1976, Pai and Rogers 1991b, Rodosky et al 1989, Roebroek et al 1994, Shepherd and Gentile 1994). The extension moment may change to flexion as the movement nears completion (Carr and Gentile 1994, Rodosky et al 1989, Roebroek et al

The use of the arms also affects the kinetics of rising to stand from a chair. Push from the hands reduced hip and knee extension moments (Arborelius et al 1992, Burdett et al 1985, Schultz et al 1992). When arm movement is restricted such as when the arms are held crossed over the chest, investigation of joint powers at the knee also showed that more work was being done over a longer period of time, thus compensating for the loss of propulsive force when the arms are restricted (Carr and Gentile 1994).

Kinetics of the sit-to-stand motion are also affected by the initial position of the feet and trunk. With feet in a preferred position, anteriorly directed GRF was significantly reduced and the pattern of vertical GRF was altered (Stevens et al 1989). As the feet are placed further forward the peak hip extension moment increases and the peak knee extension moment decreases (Fleckenstein et al 1988, Koh 1992). Relative timing of the ankle, knee and hip peak moments appears also to be affected by foot position. Where the foot is placed such the ankle is initially dorsiflexed, peak lower limb joint moments occur simultaneously (Koh 1992, Roebroek et al 1994). Whereas if foot position is such that the
shank is initially perpendicular, they peak sequentially, hip first followed by knee then ankle (Koh 1992).

The sit-to-stand motion cannot be successfully completed unless the body's centre of mass is brought forward from its location in the seated position to a location over the feet (Schultz et al 1992). Therefore any segment movement which contributes to this relocation of the body's centre of mass must be considered in relation to the segment's contribution to the total movement. The majority of segment kinetic investigations have been related to the lower limb and head-arm-trunk segment unit. However, although the head-arm-trunk segment unit is thought to be the major contributor to the horizontal maximum linear momentum (Pai and Rogers 1991a, Roebroek et al 1994), the contribution to sit-to-stand motion kinetics and dynamic analysis during the sit-to-stand motion of the individual head, trunk and upper limb segments have been rarely investigated. Schultz et al (1992) calculated that in the seated position, flexing the head and neck 45°, stretching the upper limb forwards and upper body flexion will bring the location of the total body centre of mass forwards 0.6cm, 4.2cm, and 8.1cm respectively. Although these contributions to altered total body centre of mass position may be small the significance of these segments' contribution to the overall kinetics of the sit-to-stand motion is unknown. Interestingly, it appears forward movement of the arms is concomitant to lower limb movement as when a subject's arm movement was instructed to be limited but not precluded, significant arm usage still occurred (Carr and Gentile 1994).

Consistency of performance from trial to trial of the vertical and anterio-posterior ground reaction forces and frontfoot-rearfoot vertical force symmetry is thought to be good (Crosbie et al 1997, Durward 1994) while inter trial consistency of the symmetry between the left and right sides for the vertical ground reaction force is poor (Durward 1994). Hesse
et al (1996) reported that while some subjects show a preference for use of one limb during rising to stand, in that the vertical force under one limb was always greater than the other, many subjects do not show a clear limb preferences. In addition the centre of gravity was always displaced to the right after seat off for some subjects, however the majority of subjects showed no preferences and displaced the centre of mass to either the left or the right (Hesse et al 1996). Furthermore principal component analysis has shown that the first principal component, which explains approximately 63% of the variance in ground reaction forces during rising to stand, is not dependant on the lateral force (Borzelli et al 1999) and therefore more variability may be expected in the lateral forces. It is possible therefore that the test to test consistency of performance for the vertical and anterio-posterior ground reaction forces would be greater than that for the mediolateral forces.

Variability in joint moment data may be attributed to calculations involving double differentiation to calculate acceleration, or variability on the digitising process used in the collection of kinematic data subsequently used in kinetic calculations (Bridson 1993) as well as natural human variability. Therefore trial to trial variability may be expected. Jevsevar et al (1993) however, reported no trial to trial statistically significant differences in the peak knee joint moment during the sit-to-stand motion. Crobie et al (1997) also reported a relatively low within subject coefficient of variance for the ankle, knee and hip moments when rising to stand. The test to retest stability of the lower limb joint moments, however, remains unknown.
Movement symmetry and motion in the coronal and transverse planes

Sit-to-stand has frequently been assumed to be a symmetrical activity occurring in the sagittal plane for the purpose of modeling the movement (Nuzik et al 1986, Pai and Rogers 1991a, Roebroek et al 1994). Where kinematic and kinetic studies have included data from both sides of the body, however, some studies have reported no significant difference between right and left sides during sit-to-stand (Jevsevar et al 1993, Schenkman et al 1990, Wheeler et al 1985) while others have reported asymmetries (Durward 1994, Hesse et al 1996, Lundin et al 1995, Rodosky et al 1989). Asymmetry may also vary during different phases of the rise to stand motion (Hirschfeld et al 1999). Asymmetry is not related to limb dominance and is variable between individuals (Hesse et al 1996). Thus individual strategies may exist for using the right and left sides during rising (Hesse et al 1996).

A combination of mediolateral and antero-posterior ground reaction forces, with asymmetry between the left and right ground reaction forces may indicate that coronal and transverse displacements and moments may have occurred in the lower limb joints and lateral or transverse trunk motions. Lateral shoulder and pelvis movements during sit-to-stand have been reported (Anglin and Wyss 2000, Baer and Ashburn 1995). The direction of the shift occurred randomly to either side (Baer and Ashburn 1995) supporting the concept of individual symmetry strategies. Krebs et al (1992), however, reported very little lateral or transverse plane trunk motion. It is possible that as mass and trunk dimensions increase as pregnancy progresses that changes may occur in motion symmetry and coronal and transverse plane motion. Coronal and transverse plane movement may also occur as a strategy to overcome limited forward flexion.
Constrained versus unconstrained upper limb motion

Much of the research to date has examined a constrained sit-to-stand motion in that the subjects are asked to rise with arms folded and kept as close to the body as possible (Crosbie et al 1997, Jevsevar et al 1993, Kralj et al 1990, Krebs et al 1992, Pai and Rogers 1991a, Riley et al 1991, Rodosky et al 1989, Schenkman et al 1990). This methodology has been used in order to limit the effects of arm motion on the movement (Pai and Rogers 1991a). The use of the upper limbs (Carr and Gentile 1994), and initial foot position (Khemlani et al 1999), however, have been found to significantly affect both kinetic and kinematic variables and movement strategies, and these factors are not typically restricted in the everyday activity of rising to stand from a chair. Carr (1992) also suggests that the arms should be free to move when investigating individuals who have difficulty in generating sufficient muscle force to complete the motion. This may apply to subjects in late pregnancy. The development of an arm use strategy, however, where subjects are encountering a progressively altering body shape and increasing mass is unknown.


**Pregnancy and the immediate postbirth period**

During pregnancy the female body must accommodate the enlarging gravid uterus and increases in weight. As the pregnancy progresses, therefore, the maternal musculoskeletal system is required to adapt in both morphology and functional workload. After childbirth there is a rapid change in both mass and dimensions requiring further adaptations. As pregnancy is a part of the normal lifespan for many females, the effect of these adaptations on posture and the ability to perform tasks is important. Furthermore these adaptations represent a normal life process rather than a disease or result of trauma and as such are an important part of understanding the complexity of the human musculoskeletal system.

**Morphological Adaptations**

Morphological adaptations to pregnancy are conspicuous in the trunk, although not limited to it. Trunk dimensional adaptations to pregnancy include increased thoracic diameters (Gilroy et al 1988), increased abdominal circumference (Ostgaard et al 1993, Yamana et al 1984), trunk depth (Ostgaard et al 1993, Yamana et al 1984) and transverse diameters (Ostgaard et al 1993) although there are no changes in lengths (Yamana et al 1984). Trunk dimensional increases are also accompanied by adaptations in abdominal muscle structure with increased abdominal muscle length (Fast et al 1990, Gillear and Brown 1996), and diastasis Recti Abdominis (Boissonnault and Blaschak 1988, Bursch 1987, Gillear and Brown 1996) leading to change in the abdominal muscles' angle of insertion in both coronal and sagittal planes (Gillear and Brown 1996).

As pregnancy progresses the gravid uterus and its contents increases in mass and there is also increased deposition of adipose tissue (Villar et al 1992). Consequently there is an increase in body segments' mass although the increase is not uniform across all body segments and there are substantial inter-individual differences (Jensen et al 1996a). The
lower trunk segment shows the greatest changes in mass, position of centre of mass and principal moments followed by the upper trunk and thigh (Jensen et al 1996a).

Postbirth, the mass of the lower trunk segment may be assumed to decrease as it no longer contains the foetus and uterine contents. Skinfold thicknesses during the first month postbirth, however, show a high correlation with skin folds in late pregnancy indicating that subcutaneous adipose tissue laid down in pregnancy may be retained postbirth (Ridzon et al 1998). No studies have investigated the inertial parameters of the body segments in the post-birth period.

Increased trunk dimensions may limit range of movement of the hip joint, and trunk segments. This in combination with altered inertias may alter the kinematics of body segments during both trunk movements and functional activities such as rising from a chair during pregnancy. These changes may also persist into the post-birth period.

**Joint Laxity**

Reported difficulties in postural tasks and daily activities during pregnancy may be related to several factors including problems with mobility, back and lower limb pain, reach or clearance (Nicholls and Grieve 1992a). Possible explanations for the underlying mechanisms have been proposed including geometric constraints, lack of stability or hormonal influences on ligament laxity (McNitt-Gray 1991, Poole 1998). The hormone relaxin has long been associated with pelvis ligament relaxation in rodents (MacLennan 1983). The effects in humans, however, are equivocal. Some studies have reported an increased serum level of relaxin in patients with backpain during pregnancy (Kristiansson et al 1996, MacLennan et al 1986) while others have reported no relationship (Hansen et al 1996, Petersen et al 1994). Correlations between increased progesterone and oestrogen with pelvic pain have also been reported (Golighty 1982, Kristiansson 1996). Support for
the idea of joint laxity in pregnancy was gained from the results of radiographic studies in the 1930s and 40s which showed increased width of the sacroiliac joints and symphysis pubis during pregnancy (Young 1940). More recently however, Ostgaard et al (1992) have reported no increased mobility in the pelvic joints in patients with pelvic girdle relaxation. Hormonal effects on the peripheral joints have also been investigated by repeated tests of flexibility on knee ligaments (Dumas and Reid 1997, Schauberger et al 1996) and finger laxity (Ostgaard et al 1993, Schauberger et al 1996) as pregnancy progressed and when comparing late pregnancy to postbirth (Calguneri et al 1982, Dumas and Reid 1997, Schauberger et al 1996). Again as with the effect of hormones, the results are equivocal. For the knee joint, Schauberger et al (1996) found increases in knee joint laxity from prepregnancy levels continued as pregnancy progressed, then falling postbirth but not to prepregnant levels by six weeks post partum. Dumas and Reid (1997) using the same type of arthrometer but a lower load, found no effect of pregnancy between early and late gestation, however, postbirth the laxity was significantly decreased. Finger joint laxity was found to be increasing over pregnancy relative to prepregnancy values, (Schauberger et al 1996), and increases between early and late pregnancy were also reported (Ostgaard et al 1993). Decreases in finger joint laxity are seen in the postbirth period (Calguneri et al 1982, Schauberger et al 1996), however again they were higher than prepregnancy values (Schauberger et al 1996). It is possible that, although different protocols have been used by the different studies, effects on peripheral joint laxity may occur very early in the pregnancy. In addition, there is further evidence from the work of Calguneri et al (1982), and Ostgaard et al (1993), on finger joint laxity during subsequent pregnancies, that the body may not re-establish the nulliparous state after the first pregnancy. Continuing effects
of pregnancy, however, is disputed by Dumas and Reid (1997) who found there was no significant effect of subsequent pregnancies on knee joint laxity.

**Posture in Quiet Standing**

A prevailing theme evident in much of the anecdotal reports on pregnancy is that there is an increase in spinal curvatures for quiet standing postures as pregnancy progresses. Research results however are equivocal. Alterations in pelvic inclination (Franklin and Conner-Kerr 1998), lumbar (Bullock et al 1987, Bullock-Saxton 1991, Dumas et al 1995, Moore et al 1990, Otman et al 1989, Snijders et al 1984, Thitilertdecha 1994) and thoracic curvatures (Bullock et al 1987, Bullock-Saxton 1991, Otman et al 1989, Snijders et al 1984) have been reported. The reports differed as to whether there was an increase or decrease in lumbar curvature and the extent of changes in curvatures was also a matter of debate. Other investigations have reported no significant change in pelvic inclination (Bullock et al 1987), sacral base inclination (Franklin and Conner-Kerr 1998), thoracic kyphosis (Dumas et al 1995, Franklin and Conner-Kerr 1998, Moore et al 1990, Thitilertdecha 1994) and lumbar lordosis (Ostgaard et al 1993). The use of different study designs and measurement techniques make comparison of these studies difficult. Moore et al (1990), and Bullock-Saxton (1991), however, also reported that individual subjects showed different postural behaviours with some increasing and some decreasing their lumbar lordosis. Quiet standing postural adaptations may therefore be individual in nature and the assumption of increased spinal curvature as pregnancy progresses in all women may be erroneous.

The centre of gravity has been described, anecdotally, as moving forwards as pregnancy progresses (Danforth 1967), although this is not supported in the literature. Moore et al (1990) and Dumas et al (1995) reported no significant change in the sagittal position of the
line of gravity. There was also no difference in position between exercisers and non-exercisers (Dumas et al 1995). Golomer et al (1991), Fries et al (1946), and Snijders et al (1984) however, reported that the centre of gravity moves posteriorly as pregnancy progressed. The transverse location is not affected by pregnancy although a small rise in the height may also occur (Fries and Hellebrandt 1946). Therefore although anecdotal comments that the centre of gravity moves forward during pregnancy are unsupported, the question of whether it remains stationary or moves posteriorly remains unresolved.

Post-birth, the gravid uterus and its contents no longer exhibit a prominent influence on the maternal musculoskeletal system. It therefore would be logical to assume that the adaptations which have occurred would be reversed. Indeed this is an implicit assumption where reports of changes in pregnancy are the result of comparison with post-birth results. Diastasis Rectus Abdominis has been shown to be reversing, with significant reduction by four weeks post-birth (Gilleard and Brown 1996). The abdominal muscle test results of Gilleard and Brown (1996), however, indicate that all structural adaptations as a result of the pregnancy may not be completely reversed by eight weeks post-birth. Otman et al (1989) report six weeks post-birth lordotic curvature during standing values were still increased relative to first trimester values and Dumas et al (1995) and Moore et al (1990) found increased lordosis postbirth was relative to late pregnancy. Bullock-Saxton (1991) also found no significant changes in lumbar and thoracic curvatures and pelvic inclination between late pregnancy and 6 to 12 weeks post-birth. The effects of pregnancy on postural changes therefore may persist after the delivery.

Trial to trial stability of lumbar and thoracic curvatures and pelvic inclination measurements in early pregnancy have been reported as high (Bullock et al 1987) which concurs with results in non pregnant females (Bullock et al 1987, Chaipackdee et al 1993,
Variability in standing posture, however, in pregnant subjects appears to be high with relatively large variances reported in several studies (Bullock et al 1987, Bullock-Saxton 1991, Franklin and Conner-Kerr 1998, Moore et al 1990).

**Biomechanics of seated and standing tasks**

As pregnancy progresses women report difficulties in postural activities such as working at a desk (Nicholls and Grieve 1992a). Although posture of the trunk in quiet standing has been investigated by several authors, as discussed above, relatively few studies have investigated the biomechanics of postural tasks in pregnancy. For seated posture during working at a word processor (Lee et al 1999, Nicholls and Grieve 1992b) and standing posture during an assembly task (Paul et al 1996) the maternal subjects' angle of trunk forward inclination increased as pregnancy progressed. The increased trunk angulation was thought to be needed to allow for reduction in reach zone arising from increased abdominal depth (Lee et al 1999, Nicholls and Grieve 1992b, Paul et al 1996). Further support for this hypothesis was seen in another study by Paul and Frings-Dresen (1994) where postbirth the standing posture measures returned to non-pregnant values. Several of these studies modeled the trunk as a single segment assuming the inclination occurred at the hip joint (Nicholls and Grieve 1992b, Paul and Frings-Dresen 1994, Paul et al 1996). It is possible, however, that a differential exists between the inclination of the upper and lower trunk as the gravid uterus would resist forward motion of the lower trunk particularly in sitting. Lee et al (1999) reported that for a seated workstation task the increase in trunk angulation during pregnancy was achieved by rounding the shoulders. Thus it is possible that there is more musculoskeletal demands on some areas of the trunk than others.

Hip joint moments created by the standing assembly task increased as pregnancy progressed (Paul et al 1996). The reactive moments at the hips increased 2.8 (SD 1.2) times
from 10 weeks gestation to 40 weeks. Also the 95% confidence intervals increased indicating increasing difference between individuals as pregnancy progressed (Paul et al 1996). The large increase in hip joint moments was thought to be principally due to postural changes related to increased dimensions rather than the effect of increased load (Paul et al 1996). Snijders et al (1984), however, reported for stooping forward during pregnancy, the increased moment at the hip was accounted for by increased trunk weight. Changes in body balance may also be expected as mass increases and its distribution changes during pregnancy (Oliveira et al 1997). No significant changes in postural sway were found when eyes were closed or open, nor when width of the base of standing support was altered for quiet standing (Oliveira et al 1997). Therefore it seems that the mechanisms of balance control were able to compensate for the morphological adaptations of pregnancy (Oliveira et al 1997).

**Biomechanics of movement tasks**

Motion of the pelvis segment and lumbar spine during trunk motion of forward flexion and lateral flexion to the right and left sides while standing was investigated by Dumas et al (1998b). Decreases in range of motion occurred between prepregnancy and late gestation and were thought to be related to increased abdominal dimensions. Postbirth the range of motion returned to prepregnant values by 16 weeks after delivery for pelvis forward flexion and lumbar spine lateral flexion. The lumbar spine range of motion in forward flexion, however, was significantly increased 16 weeks postbirth relative to prepregnancy values. This increase was thought to be due to the continuing effect of pregnancy on joint laxity (Dumas et al 1998b). Unfortunately no control group was used to investigate the effect of repeated tests and the variance of the results was not reported. The effect of repeated testing over such a time is unknown. It is possible that familiarisation with the test may
produce increased range of motion as the six week postbirth test was similar to the prepregnancy results.

Knee joint kinetics, hip moments, and temporal aspects of rising to stand from a chair during pregnancy have also been reported (Ellis et al 1985, Hirao and Kajiyama 1994, Jensen et al 1996). Difficulty in rising to stand from a chair was reflected in an increased time to rise both when using arm rests and pushing off from the seatpan (Hirao and Kajiyama 1994). Knee joint forces, quadriceps muscle forces and hip joint moments were also increased in late pregnancy (Ellis et al 1985, Jensen et al 1996). The increase in hip moment was thought to be primarily the result of increased mass particularly at the beginning of the hip extension phase (Jensen et al 1996). Ellis et al (1985) also noted that women, when not using armrests, appear not to incline the trunk forward in late pregnancy unlike non-pregnant subjects although kinematic measurements were not reported.

**Trunk muscle function**

Alterations in posture and difficulties in trunk movement as a pregnancy progresses and post-birth have been ascribed to weakened abdominal muscles (Danforth 1967). There is, however, conflicting evidence of abdominal muscle functional abilities during pregnancy and postbirth. Gilleard and Brown (1996) showed that the ability of the abdominal muscle group to stabilise the pelvis against resistance in a supine position decreased as pregnancy progressed. Gilleard (1997) reported that the ability to produce trunk flexion force when standing for women at mid and late pregnancy was not significantly different to non-pregnant women. Postbirth, Gilleard and Brown (1996) and Gilleard (1997) reported decreased abdominal muscle functional capabilities, however, Jackson and Kleinig, (1991) reported no differences. These studies all used functional tests that were not confounded by movement obstruction by the gravid uterus, therefore the results may be considered to be
true indicators of muscle function (Gilleard and Brown 1996). The conflict of results, however, may be related to the use of longitudinal and cross-sectional designs, and different muscle function tests.

Back pain during pregnancy and postbirth has been thought to be related to the fatigue of the back muscles (Dumas et al 1998a). The fatigability of the Erector Spine in the mid thoracic and mid lumbar spine, however, was found to be significantly increased postbirth relative to pre pregnancy values (Dumas et al 1998a). The increase was thought to be due to the training effect of carrying and looking after a baby (Dumas et al 1998a).