Coordinated Ground Forces Exerted by Buttocks and Feet are Adequately Programmed for Weight Transfer During Sit-to-Stand

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Coordinated ground forces exerted by buttocks and feet are adequately programmed for weight transfer during sit-to-stand. J. Neurophysiol. 82: 3021–3029, 1999. The purpose of this study was to test the hypothesis whether weight transfer during sit-to-stand (STS) is the result of coordinated ground forces exerted by buttocks and feet before seat-off. Whole-body kinematics and three-dimensional ground forces from left and right buttock as well as from left and right foot were recorded for seven adults during STS. We defined a preparatory phase from onset of the first detectable anterior/posterior (A/P) force to seat-off (buttock forces fell to 0) and a rising phase from seat-off to the decrease of center of mass (CoM) vertical velocity to zero. STS was induced by an increase of vertical and backward directed ground forces exerted by the buttocks that significantly preceded the onset of any trunk movement. All ground forces peaked before or around the moment of seat-off, whereas all kinematic variables, except trunk forward rotation and hip flexion, peaked after seat-off, during or after the rising phase. The present study suggests that the weight transfer from sit to stand is induced by ground forces exerted by buttocks and feet before seat-off, i.e., during the preparatory phase. The buttocks generate the isometric “rising forces,” e.g., the propulsive impulse for the forward acceleration of the body, while the feet apply adequate damping control before seat-off. This indicates that the rising movement is a result of these coordinated forces, targeted to match the subject’s weight and support base distance between buttocks and feet. The single peaked, bell-shaped profiles peaking before seat-off, were seen beneath buttocks for the “rising drive,” i.e., between the time of peak backward directed force and seat-off, as well as beneath the feet for the “damping drive,” i.e., from onset to the peak of forward-directed force and for CoM A/P velocity. This suggests that both beginning and end of the weight transfer process are programmed before seat-off. The peak deceleration of A/P CoM took place shortly (~100 ms) after CoM peak velocity, resulting in a well controlled CoM deceleration before seat-off. In contrast to the view of other authors, this suggests that body equilibrium is controlled during weight transfer.

INTRODUCTION

Rising from a seated position requires forward and upward displacement of the body’s center of mass (CoM) to transfer the body mass over the feet. As the support base is narrowed down to the area limited by the feet, concomitantly with the displacement of CoM, the CNS is challenged to control both whole-body movement and body equilibrium at the same time. Body equilibrium seems to be particularly threatened directly after seat-off (Schultz et al. 1992), as the center of pressure (CoP) is then under the heels having just moved backward before seat-off, while CoM is ~70 mm behind CoP (Schenkman et al. 1990). Also, the transition from forward to upward velocity of CoM takes place around seat-off (Millington et al. 1992). Forward rotation of the upper body contributes to the horizontal velocity, whereas extension of the hips and legs is primarily responsible for the vertical velocity (Roebroeck et al. 1994). Pai and Rogers (1990) have showed that peak horizontal momentum was relatively constant across a range of movement speeds, suggesting that the initial propulsive impulse may be an important factor for the regulation in dynamic tasks such as sit-to-stand (STS).

Studies on normative data of STS have evaluated kinematics, kinetics, muscle activation, and trunk forward momentum during the weight-transfer phase (Doorenbosch et al. 1994; Kelley et al. 1976; Kotake et al. 1993; Riley et al. 1991; Rodosky et al. 1989; Roebroeck et al. 1994; Rogers and Pai 1990; Stevens et al. 1989) but not during the initiation of an STS task, i.e., before seat-off. The reason may be that the analysis of ground reaction forces (GRF) has been limited to one or two force plates (Doorenbosch et al. 1994; Riley et al. 1991; Roebroeck et al. 1994; Schauer et al. 1993) primarily focusing on the vertical ground reaction force, the anterior/posterior (A/P) shear force beneath the feet, and on the calculation of joint moments. Although Schauer et al. (1993) used two force plates in their experimental setup with one plate beneath the sitting device and the other beneath the feet, the analysis of the force signals from both plates was limited to focusing on the total CoP displacement.

Crenna and Frigo (1991) have shown that during STS, the initial backward displacement of CoP beneath the feet has characteristics similar to those of motor programs of other forward-oriented movements, such as throwing a ball or initiation of gait. Horizontal displacement of CoM in association with a reduction of the support base during gait initiation or one leg lift has been investigated by several researchers (Brenière et al. 1981; Rogers and Pai 1990). It has been shown that CoM displacement toward the stance leg and flexing of the lifting leg are programmed before the visible movement. Lift-off is preceded by a preparatory adjustment during which the load on the lifting leg increases simultaneously with the application of a laterally directed force, thereby inducing CoM displacement toward the stance leg. The height of a vertical jump depends on the magnitude of CoM vertical velocity at “take-off,” which in turn is determined by the vertical ground reaction force (Enoka 1994; Miller 1976). Transferred to STS, decreasing the support base from four supporting corners during sitting to two during standing requires the generation of...
ground reaction forces inducing the forward and upward movement of CoM. Theoretically, this can be accomplished if buttocks and feet cooperate in exerting backward and downward directed forces for generating the propulsive impulse and if the feet exert forward-directed forces after seat-off to generate the braking impulse.

By using four force plates, two positioned beneath the buttocks and two beneath the feet, in combination with whole-body kinematics, we wanted to focus on the processes responsible for STS initiation. We hypothesized that the weight transfer is programmed before seat-off. Accordingly, the onset latency of ground forces exerted by the buttocks will precede the onset of trunk movement and the CoM forward velocity will be coordinated to the forces exerted by the feet. The results have proved to support this hypothesis.

METHODS

Subjects

Seven healthy adult subjects, four women and three men, participated in this study. Their mean age was 24.1 ± 3.9 (SD) yr; their mean height and weight was 178.3 ± 9.3 cm and 71.3 ± 9.4 kg, respectively. The study was approved by the local ethics committee, and the subjects received written information about the procedure and signed consent was obtained from each subject.

Procedure

Subjects sat on two force plates placed on a table. Their bare feet were positioned on two other force plates placed on an adjustable platform. Seat height was standardized at the knee joint line with the subject in standing and adjusted by lowering or raising the platform. No other restrictions were imposed on the initial position. An auditory signal from the computer cued the subject to initiate the task. The subjects were asked to perform the task in a comfortable and natural manner and at a self-selected speed. However, problems with occlusion of markers by the arm made it necessary to ask the subjects to cross their arms in front of the body, holding the left hand loosely around the right wrist. The task was performed in two blocks of five trials preceded by three practice trials.

Instrumentation and data analysis

Synchronized kinematic and force plate data were used to examine the STS task. Signals were digitized with an A/D converter at a frequency of 100 Hz and sampled for 5 s for each trial. Before onset of the auditory signal, 500 ms of baseline data were recorded. The digitized data were stored for further processing.

KINEMATICS. A two-camera optoelectronic system (ELITE, BTS, Milan) was used to record the kinematics. The two charged couple device (CCD) cameras were placed above each other orthogonally to the sagittal plane. The setup is shown schematically in Fig. 1, including the coordinate system and marker locations. The cameras were aligned vertically, perpendicular to the sagittal plane.

FIG. 1. Schematic drawing of the experimental set-up. Stick figure, showing marker numbers as defined in METHODS, was copied from the Elite tracking data file. Note the 3-dimensional reference coordinates for kinematics (Elite system) and force plates. Cameras were aligned vertically, perpendicular to the sagittal plane.

The setup was defined by joining markers as follows: hip joint (15–18) were attached onto the corners of the force plates for spatial reference. The body markers defined the positions of 12 body links used for kinematic analyses and computation of the CoM. CoM was computed for each subject by means of a special software using length and circumference measurements and average density (g/cm³) of the defined body links. CoM subsequently could be visualized in the kinematic data files as an additional marker and used for calculating linear displacement and velocity of CoM. Similarly, linear displacement of the head was calculated from marker 1. The following angular displacements were measured: rotations of trunk and pelvis segments versus the horizontal axis; trunk segment was defined by joining markers 3 and 5, and pelvis segment by joining markers 6 and 7; joint angles for hip, knee, and ankle by measuring an angle between two intersecting links formed by joining markers as follows: hip joint angle between the links 6–7 and 7–8, knee joint between links 7–8 and 8–9, and ankle joint between links 8–9 and 10–11 (see Fig. 1). Velocity (dP/dt) of CoM was computed by using a ±10 point numerical differentiation.

FORCE PLATES. The ground reaction forces were recorded by means of four equal force plates (AMTI, Advanced Mechanical Technology; model MC818-6-1,000; size 457 × 203 mm; accuracy 0.25N). The distance between the plates was 40 mm. Three orthogonal forces, Fx (A/P shear), Fy [medial/lateral (M/L) shear], and Fz (vertical), were measured for each force plate (see coordinate system in Fig. 1). The amplitudes of the force signals were normalized by body mass and are expressed as a percentage change of body weight (%BW). It should be noted that in this study the forces are described in accordance with their application, i.e., as forces applied to the ground by the buttocks and/or the feet, and will consequently be referred to as ground forces (GFs).

DATA ANALYSIS. Using a ±10 point numerical differentiation, force rate (dP/dt) was computed. Recordings of GFs and kinematic data were transformed into ASCII files and analyzed by means of Axograph (Axon Instruments), a Macintosh-based software package. Be-
fore analyses, digital filtering for signal smoothing was performed for all signals. Axograph provides a digital filter by convolving a Gaussian envelope with the data. A filter cutoff frequency of one-fifth of the sampling frequency was selected. Subsequently, the graphics terminal was used to define temporal events and peak amplitudes. The first seven trials per subject that were free of technical problems were analyzed (= 49 trials).

All temporal events were defined with respect to the time at which the thighs lost contact with the seat as indicated by vertical force on the right side. That instant was set at zero time and referred to as seat-off. Latencies of kinematic and force events were determined manually from Axograph for each trial by selecting one trace display with a time window of 1,000 ms before and 1,000 ms after seat-off with a zero crossing axis. Onset latency of displacement was identified from cursor read outs of a continuous divergence from baseline, which lasted >100 ms, and onset latency of ground forces was a continuous divergence of force above or below the baseline that lasted >100 ms. Peak amplitudes of kinematics were computed as changes relative to the initial sitting position and of ground forces as the amplitude of final minus initial force. When the subject’s initial sitting position was examined, Axograph was used to calculate the baseline mean (500 ms) for segment and joint angles and for the exerted forces at each force plate during initial sitting. For the force vector analysis, we defined a window of 200 ms after onset of each M/L force, respectively, where the mean amplitude of A/P and M/L forces were measured. This time frame was chosen based on the duration of the M/L force exerted by the feet before seat-off. The duration of the STS task, or movement time, was defined as the duration from the start of force change beneath the buttocks (A/P on right side) to the moment in time when deceleration of CoM vertical velocity reached zero. Average movement time for all trials, as well as means for each subject, were calculated. For other variables, means and standard deviations were calculated for all 49 trials. One-way ANOVA with repeated measures was used to compare means. Significance level was set at $P < 0.05$, and the Tukey HSD post hoc procedure was used to analyze significant differences. Correlations were tested by means of the Pearson product-moment correlation test.

**RESULTS**

**Initial sitting posture**

During initial sitting (measured during 500 ms before onset of rising signal), all subjects supported ~85% of body weight (BW) on the buttocks and ~15% of BW on the feet. The weight distribution, however, was not symmetrical. Subjects bore significantly more weight on the left buttock (Table 1). All subjects exerted shear forces in the A/P as well as medial/lateral M/L direction (Table 1) with the feet pushing outward and forward and with the buttocks pushing backward and outward. The magnitudes of the A/P force were significantly larger beneath the right buttock and foot compared with those beneath the left ($P < 0.05$). The sagittal segment and joint angles during initial sitting did not differ between subjects

<table>
<thead>
<tr>
<th>Segment</th>
<th>Joint Angle (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trunk</td>
<td>81 ± 2</td>
</tr>
<tr>
<td>Pelvis</td>
<td>115 ± 7</td>
</tr>
<tr>
<td>Hip joint</td>
<td>130 ± 8</td>
</tr>
<tr>
<td>Knee joint</td>
<td>89 ± 5</td>
</tr>
<tr>
<td>Ankle joint</td>
<td>76 ± 4</td>
</tr>
</tbody>
</table>

Means ± SD (49 trials) of segment and joint angles measured in sagittal view over the same time window. See Fig. 5 for the definition of angles measured.

($P > 0.05$, Table 2) even though the sitting posture was not standardized, except as regards seat height. Similar CoM position was regained between STS trials (12 ± 4 mm, mean difference ± SD of means) when measured as the distance between CoM position and hip position (marker on the greater trochanter) in A/P direction. The small SDs of the trunk segment angle also should be noted (Table 2).

**STS phases and movement time**

We focused the analysis on a preparatory phase and a rising phase based on the analysis of GFs and kinematics. The preparatory phase was defined as the onset of an A/P force beneath the right buttock and lasted until seat-off (time 0). The rising phase lasted from seat-off until CoM vertical velocity decreased to zero. In this study, we disregarded the stabilization phase, which takes place after rising. Movement time was defined as the combined time of the two phases. The rising speed was self-paced resulting in a movement time of 1,504 ± 169 ms (mean ± SD of all means). The preparatory phase was 54 ± 4% of total movement time. Each subject’s means of movement time along with preparatory and rising phases are shown in Table 3. Group movement time was normally distributed. However, there was significant variability between and within subjects in movement time as well as in the duration of the preparatory and rising phases expressed in percent of total movement time ($P < 0.05$). The post hoc analysis showed that differences >370 ms in movement time and 5% in the preparatory and rising phase, respectively, were statistically significant ($P < 0.05$).

**Preparatory phase**

**GROUND FORCES EXERTED BY BUTTOCKS AND FEET. Temporal pattern.** The first change in GFs seen in all subjects was an increase in loading (vertical force) and a backward directed

**TABLE 2. Average amplitude**

<table>
<thead>
<tr>
<th>Segment</th>
<th>Joint Angle (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left Foot</td>
<td>0.67 ± 0.32</td>
</tr>
<tr>
<td>Right Foot</td>
<td>0.81 ± 0.32*</td>
</tr>
<tr>
<td>Left Buttock</td>
<td>−0.49 ± 0.58</td>
</tr>
<tr>
<td>Right Buttock</td>
<td>−0.75 ± 0.42*</td>
</tr>
<tr>
<td>Fx</td>
<td>0.85 ± 1.26</td>
</tr>
<tr>
<td>Fy</td>
<td>−0.51 ± 0.43</td>
</tr>
<tr>
<td>Fz</td>
<td>7.98 ± 1.6</td>
</tr>
</tbody>
</table>

Means ± SD (49 trials) of distribution of GFs (expressed in percent body weight) beneath the feet and buttocks during initial sitting as measured >500 ms before onset of rising signal. * Significant difference of applied forces between left and right side ($P < 0.05$).

**TABLE 3. Movement time and duration of preparatory and rising phase**

<table>
<thead>
<tr>
<th>Subject</th>
<th>Movement Time, ms</th>
<th>Preparatory Phase, ms</th>
<th>Rising Phase, ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1,659 ± 78</td>
<td>920 ± 37 (56 ± 2)</td>
<td>739 ± 59 (44 ± 2)</td>
</tr>
<tr>
<td>2</td>
<td>1,576 ± 87</td>
<td>819 ± 35 (52 ± 2)</td>
<td>756 ± 63 (48 ± 2)</td>
</tr>
<tr>
<td>3</td>
<td>1,286 ± 57</td>
<td>751 ± 49 (58 ± 2)</td>
<td>535 ± 26 (42 ± 2)</td>
</tr>
<tr>
<td>4</td>
<td>1,259 ± 212</td>
<td>643 ± 117 (51 ± 5)</td>
<td>578 ± 89 (49 ± 3)</td>
</tr>
<tr>
<td>5</td>
<td>1,513 ± 125</td>
<td>880 ± 70 (58 ± 4)</td>
<td>633 ± 89 (42 ± 4)</td>
</tr>
<tr>
<td>6</td>
<td>1,549 ± 77</td>
<td>838 ± 44 (52 ± 4)</td>
<td>711 ± 55 (46 ± 2)</td>
</tr>
<tr>
<td>7</td>
<td>1,683 ± 234</td>
<td>837 ± 103 (50 ± 3)</td>
<td>846 ± 154 (50 ± 3)</td>
</tr>
<tr>
<td>Group</td>
<td>1,504 ± 169</td>
<td>812 ± 91 (54 ± 4)</td>
<td>685 ± 109 (46 ± 4)</td>
</tr>
</tbody>
</table>

Means ± SD (7 trials) are presented for each subject. Percentages are in parentheses.
force (A/P) of the buttocks; i.e., the generation of the propulsive impulse. This was followed significantly later by slightly more variable M/L forces \((P < 0.05)\). The backward and vertical GFs were initiated \(-800\) ms before seat-off. A typical pattern (average of 5 trials of 1 subject) of GFs is illustrated in Fig. 2. The average onset latencies of GFs for all subjects are shown in Fig. 3A. During the initial loading of buttocks, a period of unloading (vertical forces) beneath the feet was observed. In addition, the A/P forces beneath the feet became directed backward. An example of this is seen in Fig. 2. Onset of feet unloading started at \(87_{-6}^{+73}\) ms after onset of buttocks loading, lasting for some \(100\) ms, and ended with onset of feet loading, on average \(279_{-6}^{+26}\) ms (left) and \(311_{-6}^{+26}\) ms (right) before seat-off. Onset of feet loading was associated with onset of a forward-directed A/P force, generating the braking impulse. Average onset time of the A/P force was seen at \(257_{-6}^{+58}\) ms (left) and \(255_{-6}^{+64}\) ms (right) before seat-off. Onset latency of loading was significantly preceding the onset of shear forces on same foot \((P < 0.05)\).

Peak time for backward directed A/P forces beneath the buttocks was on average \(257_{-66}^{+69}\) (left) and \(251_{-66}^{+70}\) before seat-off. Post hoc analysis revealed no significant difference between buttocks A/P force peak times and feet A/P onset latencies. The forwardly directed A/P forces beneath the feet peaked at \(96_{-6}^{+50}\) ms (left) and \(81_{-6}^{+67}\) ms (right) before seat-off, and the vertical forces peaked at \(24_{-6}^{+26}\) ms (left) and \(32_{-6}^{+32}\) ms (right) before seat-off (Fig. 3B). The medially directed M/L forces peaked at \(113_{-6}^{+32}\) ms (left) and \(101_{-6}^{+39}\) ms (right) before seat-off.

**Spatial pattern.** Vertical forces: the average peak amplitude of loading increase at the buttocks was \(5.4_{-6}^{+2}\%\) BW (left) and \(5.8_{-6}^{+4}\%\) BW (right), similar to the peak amplitudes of unloading beneath the feet. The average peak amplitudes of feet loading occurring around seat-off were \(52_{-6}^{+5}\%\) BW (left) and \(52_{-6}^{+8}\%\) BW (right). Shear forces: Figure 4 shows the average \((\pm SD)\) of the horizontal plane force vectors amplitude and direction exerted by buttocks in 40 of 49 trials and by feet in 37 of 49 trials. In these trials, the buttocks exerted a force vector amplitude of \(6.2_{-6}^{+2}\%\) BW (left) and \(5.7_{-6}^{+2}\%\) BW (right). When describing the force vector direction in the circle coordinates, the force vector angle was \(231_{-6}^{+25} (left) and \(306_{-6}^{+21}\) (right). The force vectors direction beneath the

**FIG. 2.** Time traces (mean of 5 trials) of shear forces \((Fx, Fy)\) and vertical force \((Fz)\) for left and right buttock and feet for 1 subject. Schematic drawing (top right) indicates direction of applied force resulting in positive going traces. Force amplitudes for buttocks (gray line) and feet (black line) are expressed as a percentage of body weight. Seat-off (s-o) is indicated by the dashed vertical line. Solid lines indicate onset and end of sit-to-stand (STS) task. Preparatory phase (P) is shown to the left between the solid lines and dashed lines. The rising phase (R) is shown between dashed lines and solid lines to the right. Scale bars indicate amplitudes expressed as percentage body weight (% BW).

**FIG. 3.** Means ± SD for onset latencies (A) and peak times (B) of kinematic variables and ground forces (49 trials). Temporal events and phases are indicated on the top of the graph. Note the extended time scale in B for illuminating peak times of ground forces before seat-off and peak times for most of the kinematic variables during or after the rising phase.
buttocks had changed with \( P < 0.05 \). In the remaining 9 trials for buttocks and 12 trials for feet, the force vector directions were directed diagonally to the right or to the left side. These force patterns were seen in one to three trials in four subjects (buttock force pattern) and in one to three trials in five subjects for the feet force pattern.

In summary, increased loading and backward directed force beneath buttocks initiated the STS task and generated the propulsive impulse. Onset of forward-directed feet forces, generating the braking impulse, was closely related to peak time of buttock forces. The horizontal plane forces changed direction significantly during the preparatory phase. Compared to initial sitting, they were directed mainly medially and forward beneath the feet and more backward than lateral beneath the buttocks.

**Kinematics**

**TEMPORAL PATTERN.** Onset latency of trunk and pelvis forward rotation as well as hip and ankle joint flexion was significantly later than onset latency of GFs beneath the buttocks \( (P < 0.05, \text{ Figs. 5 and 3A}) \). The A/P forward displacement of the head and forward rotation of the trunk, in their turn, took place significantly earlier \( (P < 0.05) \) than hip flexion and pelvis forward rotation. Knee extension started 286 \( \pm \) 54 ms before seat-off. Onset latency of A/P forward displacement of the CoM occurred at 713 \( \pm \) 113 ms before seat-off and was associated with a small vertical displacement at an onset latency of 694 \( \pm \) 100 ms before seat-off. This can be seen more clearly in the velocity profiles of CoM in Fig. 7. Peak time of hip flexion was at 134 \( \pm \) 30 ms before seat-off and peak time of trunk forward rotation took place 45 \( \pm \) 36 ms before seat-off (Figs. 5 and 3B).

**SPATIAL PATTERN.** Trunk and hip reached peak amplitudes during the preparatory phase while pelvis and ankle reached their peaks during the rising phase. Average peak amplitudes of segment and joint angles are shown in Table 4.

In summary, onset of kinematics came significantly later than onset of buttock forces. Trunk forward rotation and hip flexion peaked before and ankle flexion just after seat-off.

**FIG. 5.** Time traces (mean of same 5 trials as shown in Fig. 2) of linear and angular displacement of body segments. Angle conventions are indicated to the right. Arrow highlights positive going traces. Temporal events and phases are indicated on top.


Onset of CoM A/P displacement was associated with a minor vertical displacement, whereas the main vertical increase occurred some hundred ms later.

Rising phase

GROUND FORCES. Vertical forces beneath the foot decreased from 52 ± 7% BW around the time of seat-off to body weight toward the end of the rising phase (Fig. 2). After seat-off, the feet also started to exert steady, outward directed (M/L) forces and the forward-directed (A/P) forces (Fig. 2) decreased and thereafter oscillated around zero.

KINEMATICS. Head forward displacement, pelvis forward rotation and ankle flexion peaked during the rising phase, whereas CoM forward displacement and knee extension occurred some hundred ms later.

Anterior/posterior force rate pattern and CoM velocity

We analyzed temporal and spatial force rate \( \frac{dF}{dt} \) variables to investigate the interaction of backward directed forces exerted by the buttocks, generating the braking impulse and the forward-directed forces exerted by the feet, generating the braking impulse. The graph shows the relationships between force rate and knee flexion for left foot and buttock in Fig. 6A.

**TABLE 4.** Average peak amplitude of angular displacement during preparatory and rising phase

<table>
<thead>
<tr>
<th>Segment/Joint</th>
<th>Preparatory Phase, deg</th>
<th>Rising Phase, deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trunk forward rotation</td>
<td>30 ± 5</td>
<td>36 ± 4</td>
</tr>
<tr>
<td>Pelvis forward rotation</td>
<td>23 ± 5</td>
<td>7 ± 3</td>
</tr>
</tbody>
</table>

Values are means ± SD for 49 trials.

The delay between peak time of positive force rate pulse exerted by the feet and the instant of switch from negative to positive force rate pulse beneath the buttocks was 52 ± 58 ms (left) and 43 ± 68 ms (right). Peak time of positive force rate pulse beneath the feet and the onset of positive force rate pulses at the buttocks was highly correlated \((r = 0.91, P < 0.05)\), just as peak time of positive force rate pulse beneath the buttocks was highly correlated to the onset of the negative force rate pulse beneath the feet \((r = 0.94, \text{left}, r = 0.81, \text{right}, P < 0.05)\). In Fig. 6C, the force rate profiles (N/s) of right buttock and right foot are plotted against A/P force (N), illuminating the bell-shaped profiles of the positive force rate pulse of buttock and foot.

VELOCITY OF CoM. The profiles for the A/P forward and vertical velocity of CoM and the force rates of A/P force exerted by the feet are illustrated in Fig. 7, showing five superimposed trials for one subject. Peak time of CoM A/P forward velocity took place 197 ± 37 ms before seat-off. Average peak amplitude was 0.53 ± 0.08 m/s. The peak
In contrast to the view of other authors (Millington et al. 1992; Rodosky et al. 1989) also divided the STS maneuver into two distinct phases from a biomechanical point of view: the forward thrust (FT) and the extension phase (EXT). The end of the FT phase is defined as being the moment when hip and ankle flexion reach their maximum. In our study, peak time for hip flexion was 36 ± 26 ms before seat-off and for ankle dorsiflexion 143 ± 63 ms after seat-off, indicating that the end of the first phase cannot be defined exactly on the basis of kinematics. Other authors have divided the STS maneuver into three or four phases, based on analysis of the intrasegmental kinematics (Riley et al. 1991; Roebrock et al. 1994; Schenkman et al. 1990). In our study, seat-off (when vertical forces exerted by the buttocks fell to 0) occurs ~80 ms later than in studies defining seat-off as the time when the A/P component of the peak forces beneath the buttocks (see Table 1A) and 60% of total movement time, or reported by Roebrock et al. (1994) when it occurred at 37% of total movement time. The difference is due to the fact that changes in ground forces take place earlier than onsets of kinematics (see Fig. 3A and Table 3). The standard deviations of the duration of the preparatory phase compared with those of the rising phase were somewhat smaller for all subjects except two in our study, and are in agreement with other authors (Pai and Lee 1994).

Kinematics

In this study, the onset of forward movement of trunk and pelvis took place significantly later than that of ground forces applied by the buttocks. Other authors have suggested that the STS task is initiated by a forward pivoting of the trunk (Doorenbosch et al. 1994; Kelley et al. 1976; Riley et al. 1991; Roebrock et al. 1994). However, these authors did not record ground forces exerted by the buttocks. In association with the onset of loading and propulsive forces beneath the buttocks, we expected the onset of pelvis forward rotation to precede, or occur simultaneously, with trunk forward rotations. However,
this was not the case, as seen in Fig. 3A. Onset of pelvis forward rotation occurred significantly later (~50 ms) than trunk forward rotation. It should be noted that because we were interested in onset latencies of trunk movement, we measured the trunk segment angle as a link between C7 and L5 versus the horizontal axis. We did not define the trunk as a link between shoulder and hip in the same way as other authors who used it only for calculating CoM (Pai and Rogers 1990; Riley et al. 1991; Roebrock et al. 1994). The somewhat earlier onset of trunk forward rotation compared with pelvis forward rotation (Fig. 4A) suggests that the measured trunk rotation is associated with a flexion (kyphosis) of the lumbar spine, causing the delay of pelvis forward rotation due to the anatomic relationship between pelvis and lumbar spine.

**Forces beneath buttocks and feet are adequately programmed for the forward and upward displacement of CoM**

The subject has somatosensory information regarding support base conditions and distance between buttocks and feet available during sitting. The shear forces exerted by each buttock and foot during initial sitting (A/P and M/L forces in Table 1 and baseline force vectors in Fig. 4) resembles the posture control principle for quadrupedal stance. The same pattern (forelimbs pushing forward and outward and hind limbs pushing backward and outward) has been reported for cats (Fung and Macpherson 1995).

CoM was positioned over the hip joints during initial sitting. This is in agreement with studies on independent sitting in healthy adults (Schoberth 1989). The initial loading of the buttocks resulted in a small upward vertical velocity increase of CoM, immediately after onset of buttock forces (see Fig. 7). It seemed to be the only available strategy for initiation of CoM velocity because a sitting subject cannot lower CoM for “take-off” in the way as before a jump “take-off” where the initial lowering of CoM increases the amplitude of CoM vertical velocity (Enoka 1994).

The buttocks exerted forces directed backward (generating the propulsive impulse), and the feet exerted forces directed forward (generating the braking impulse) before seat-off, as shown in Fig. 2. Contrary to our assumption, feet forces did not participate in the generation of the propulsive impulse because we did not find a propulsive impulse (force exerted backward) in association with loading before the onset of the braking impulse (force exerted forward), as reported by Magnan et al. 1996. During initial sitting, the feet applied a force directed forward of <1% BW (see Table 1). Its decrease to around zero, and change of direction to backward was closely related to unloading of the feet. We therefore regarded the change in feet forces as a passive force change associated with loading of the buttocks. A similar pattern occurs before lift-off during one-leg stance, where the weight transfer to the stance leg is preceded by loading of the lifting leg and unloading of the stance leg (Rogers and Pai 1990).

The buttock force vectors illustrated in Fig. 4 are significantly less outward directed and the feet force vectors are directed medially compared with initial sitting. This suggests that the decrease of outward directed force during the preparatory phase might involve activation of hip adductor muscles for controlling knee displacement in the frontal plane. Activation of hip adductor muscles during the weight transfer process has been suggested by Kelley et al. (1976) as an explanation of the early negative hip torque not associated with the relatively late onset of hip extensor muscles.

During the rising phase, the M/L forces beneath the feet increased markedly in an outward direction, suggesting that the body is trying to ensure lateral stability during the forward and vertical displacement of CoM (see Fig. 2).

Trajectory control of multijoint movements or of targeted force impulses simplifies the scaling process by combining direction, rate, and range into one functional entity (Brooks 1984; Gordon and Ghez 1987). The importance of the preservation of directional paths and their rate of change in relation to each other was recognized by Cooke (1980). Because STS is an intended movement, subjects will choose to perform the STS with the most advantageous trajectory, i.e., one in which CoM traverses in a nearly straight path with a bell-shaped (continuous) velocity profile. Such profiles indicate use of movement programming as a strategy (Brooks 1984). The velocity traces of A/P and vertical CoM displacement had such bell-shaped profiles. Within the limits of this study, we suggest that the rising movement is the result of the programmed ground forces before seat-off (Fig. 6, A–C). The principal evidence that the coordinated force generation of buttocks and feet during the preparatory phase represented the expression of central programs, was the fact that the positive going force rate pulses were single peaked and bell shaped. These rate profiles resemble the “continuous” (Brook’s term) or “bell-shaped” (Bizzi’s term) velocity profiles frequently reported for programmed intended arm/hand movements to a target position (Bizzi and Abend 1983; Brooks 1984) and the grip and load force rate profiles seen before object lift-off with precision grip (Johansson and Westling 1988). This indicates an anticipatory strategy relying on feed forward control. The positive, single-peaked force rate pulse beneath buttocks was seen for the “rising drive,” i.e., during the time from the peak of backward directed force until seat-off and beneath the feet from onset to the peak of forward-directed force (damping drive). The fact that the latency to onset of foot forward-directed force and peak time of buttock backward directed force was not significantly different, suggests that onset of rising drive (buttocks) and “damping drive” (feet) was controlled simultaneously. This rising drive was targeted to the subjects weight because the maximum positive force rate pulse matched the weight of the body parts above the seat. Anticipatory force scaling for weight transfer beneath buttocks and feet before seat-off followed the same principle found during the loading of the intended swing leg and unloading of the stance leg in studies of weight transfer from bipedal to single limb stance (Rogers and Pai 1990), gait initiation (Bremer et al. 1981). Anticipatory force scaling occurred also when lifting objects with precision grip (Johansson and Westling 1988, 1990). The isometric force increase in backward direction beneath buttocks occurred over a relatively long time (see negative force rate pulse between onset and peak of buttock force Fig. 6, A and B), compared with the time of the rising drive (~70 and 30% time, respectively). The rate profile of the isometric force increase beneath buttocks occurred in a discontinuous mode, which might suggest a feedback strategy. A similar feedback strategy can be seen during cat locomotion, where somatosensory information during the hip extension
terminates the stance phase and releases flexor activity (Grillner and Rossignol 1978) or for different inexperienced movements (Brooks 1984). However, another possibility might be that the slight oscillations (multipeaks) of the negative force rate pulse are related to slight intersegmental dynamic interactions. This interpretation then would suggest that the isometric force increase is also part of the anticipatory strategy, using an internal presentation of body weight and distance and that feedback control does not necessarily take place. The multi-peak negative force rate pulse beneath the feet, with onset shortly before seat-off and ending after rising, might be considered as expressing the slow and discontinuous decrease of the forward-directed force continuously adjusting the damping control of the CoM forward acceleration.

It seems that timing and adequate scaling of the braking impulse before seat-off is crucial for controlling body equilibrium during the weight-transfer maneuver. The peak deceleration of CoM A/P displacement took place shortly after the time of peak velocity. Thereafter, the amplitude of peak CoM deceleration decreased by 60% until seat-off. That leaves only 40% of total CoM deceleration amplitude (which reaches 0 in upright stance) to be controlled during the rising phase. This opposes Schenkman et al. (1990), who reported that CoM trajectory is 70 mm behind CoP at seat-off and as such body equilibrium is particularly threatened directly after seat-off. However, Schenkman et al. (1990), repeated by Riley et al. 1991, have defined seat-off as being when the force vector beneath the feet begins to increase, which in our study occurred ~250 ms before seat-off as defined by us (Fig. 2 and Fig. 3A). The consequence of that is that seat-off, when measured by our method, occurred ~250 ms later than when defined by the above-mentioned authors. This questions their assumption that body equilibrium is particularly threatened because CoM is 70 mm behind CoP at seat-off. When adding 250 ms to Fig. 3 in Schenkman et al. (1991), CoM and CoP are above each other when seat-off takes place. Within the limits of this study, we suggest that the STS movement is a preprogrammed movement during which body equilibrium is well controlled.

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