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Journal of Electromyography and Kinesiology 13 (2003) 239–252

JOURNAL OF ELECTROMYOGRAPHY AND KINESIOLOGY

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The sit-up: complex kinematics and muscle activity in voluntary axial movement

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Received 6 August 2002; received in revised form 9 January 2003; accepted 18 January 2003

Abstract

This paper describes the kinematics and muscle activity associated with the standard sit-up, as a first step in the investigation of complex motor coordination. Eight normal human subjects lay on a force table and performed at least 15 sit-ups, with the arms across the chest and the legs straight and unconstrained. Several subjects also performed sit-ups with an additional weight added to the head. Support surface forces were recorded to calculate the location of the center of pressure and center of gravity; conventional motion analysis was used to measure segmental positions; and surface EMG was recorded from eight muscles. While the sit-up consists of two serial components, 'trunk curling' and 'footward pelvic rotation', it can be further subdivided into five phases, based on the kinematics. Phases I and II comprise trunk curling. Phase I consists of neck and upper trunk flexion, and phase II consists of lumbar trunk lifting. Phase II corresponds to the point of peak muscle contraction and maximum postural instability, the 'critical point' of the sit-up. Phases III–V comprise footward pelvic rotation. Phase III begins with pelvic rotation towards the feet, phase IV with leg lowering, and phase V with contact between the legs and the support surface. The overall pattern of muscle activity was complex with times of EMG onset, peak activity, offset, and duration differing for different muscles. This complex pattern changed qualitatively from one phase to the next, suggesting that the roles of different muscles and, as a consequence, the overall form of coordination, change during the sit-up.

Keywords: Axial movement; Coordination; Human; Kinematics; EMG

1. Introduction

We investigated the sit-up because it represents a useful behavioral model for studying how the central nervous system (CNS) coordinates natural voluntary movements, which often involve large numbers of joints, degrees of freedom in joint motion, and muscles. Most previous studies of motor coordination focused on simple movements involving just one or a few joints, usually in one extremity. The study of coordinated movements at individual joints presupposes that the coordination of complex, multi-joint movements can be reconstructed from the summation of coordination at individual joints. Such a simplistic perspective was shown by Bernstein [8] to apply predominately to laboratory analogs of coordinated movement, rather than to natural motor behavior. Consequently, at this time there still exists little understanding of how complex movements involving multi-link kinematic chains are coordinated, particularly those involving proximal and axial muscles.

The goal of the study presented here was to identify qualitatively the different components of the sit-up that need to be coordinated for the movement to succeed or, stated another way, to identify the most critical loci of coordination in the sit-up. By the term 'coordination', we mean the imposition of a consistent, temporal or spatial relationship among different components of a movement, be those components structural (e.g. central vs. peripheral control), kinematic, or neuromuscular. By first

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doi:10.1016/S1050-6411(03)00023-3

establishing what elements of the sit-up are coordinated, we will then be able to analyze each element in detail in order to clarify the underlying mechanisms of coordination (see Ref. [16]).

Currently, relatively little is known about the coordination of natural, complex movements. Previous studies of complex axial movements focused more on their biomechanics and exercise value than on their mechanisms of coordination. For example, a number of studies examined the sit-up, to determine its exercise value [5,20–22,25,30,34] and its physiological risk [19,22,28]. Similarly, weight lifting was evaluated (e.g. Ref. [37]) to determine how to minimize the risk of back injury during its execution. However, a number of studies have examined patterns of muscle activity in complex movements [5,19–22,25,34], which has provided insight into the underlying mechanisms of coordination. The principal insight from these studies is that muscles in complex movements are not activated and deactivated simultaneously, as typically found in simpler movements involving a single extremity.

The experimental approach used in our study was to first decompose the sit-up into phases based on kinematics. Two major components of the sit-up were identified, and these were further subdivided into five ‘phases’, based primarily on trunk and leg motion. Within each phase, we also identified subcomponents that appeared to have a specific mechanical function and that might be discretely controlled by the actions of specific muscles. We also studied the pattern of muscle activity within each phase, across a number of muscles from the neck to the legs, to determine whether the activation pattern changed in each phase. We hypothesize that changes in the activation pattern across muscle populations indicate changes in CNS control of the movement.

The experimental analysis addressed four questions, based on our preliminary observation [14,15] that this movement has two distinct parts—one flexing the trunk and the other rolling the pelvis and trunk into a sitting position. The first question addressed was: does the CNS control these two parts of the sit-up differently? Because the center of gravity (CoG) is located rostral to the pelvis in the supine individual, a major subtask of the sit-up is to move the CoG caudally through the pelvic axis of rotation in order to provide the leverage necessary for the sit-up to be successfully executed. The second question investigated was: when does the CoG pass through the rotational axis in the sit-up? A substantial number of individuals, with and without neurological disorders [6], are unable to perform a complete sit-up. The third question addressed was: is there a particular (i.e. critical) point in the sit-up at which the sit-up will most likely fail without the appropriate coordination? Finally, previous qualitative analyses of muscle activity during the sit-up have shown this activity lacks simultaneity. The fourth question addressed was: does the intramuscular pattern of muscle activity change significantly during the sit-up? Such changes would indicate the presence of serial control, in addition to the more typical parallel control observed in simpler movements.

Preliminary reports of this study have been presented in abstract form [14,15], and a review of complex movements has been published as a book chapter [16].

2. Methods

Eight human subjects (ages 18–49; five, male; three, female) with no known neuromuscular disorders participated in this study after signing an informed consent form approved by the OHSU Institutional Review Board. Subjects accepted into the study were relatively fit and capable of performing sit-ups without difficulty. Each subject—wearing brief shorts and, in the case of female volunteers, a sports bra (Fig. 1)—lay supine upon a force plate, on a force table. Recordings were made of horizontal and vertical forces, segmental kinematics, and muscle activity (EMG) during the performance of unconstrained sit-ups.

2.1. Motor task

Each subject sat up, with the legs straight and unconstrained (Fig. 1) and the arms folded across the chest to avoid their use. To achieve consistency in kinematics across subjects, sit-up duration was constrained to 3 s, a comfortable speed that is slightly slower than the speed preferred by most individuals. The subjects were assisted in producing the 3-s sit-up by a sequence of four audible tones, with each tone separated from the next by 1.5 s. The subjects were instructed to begin sitting up coincident with the second tone and to reach a sitting posture on the fourth tone. While average sit-up durations varied from one subject to another (see Table 1), each subject was sufficiently consistent so that $<10\%$ of the trials had to be repeated because of timing discrepancies. Rest periods of >30 s between sit-ups insured that the subjects were not fatigued by the exercise. All subjects performed at least 15 sit-ups in the experimental session.

At the end of the initial 15 sit-ups, three of the eight subjects performed an additional sequence of 5–10 sit-ups with a weighted belt attached to the head, to make the sit-up more difficult. The total weight of the belt was 3–5 kg, based on an estimate of the subject’s conditioning and calculated to produce a failure on the first or second sit-up. These ‘weighted’ sit-ups allowed us to determine the point during sit-ups that failures tend to occur. With one subject who failed to sit up after several attempts, the initial head weight was reduced slightly. A spotter assisted these three subjects in lying back down at the end of each weighted sit-up, to ensure that they

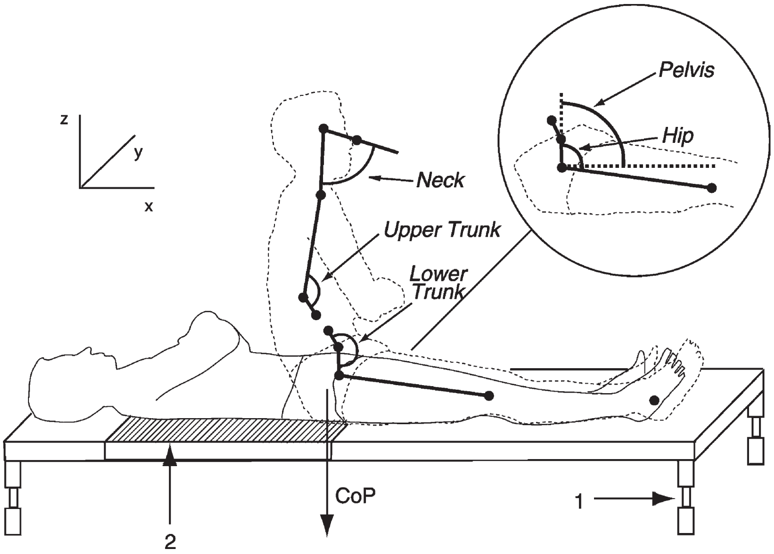

Fig. 1. Experimental set-up. The subject lay supine on the force table with the back and pelvis on the contact device (‘2’). Strain gauges measured force at each leg of the table (‘1’). Ten reflective markers were adhered to the subject’s right side in the locations shown in the figure. Five segmental angles used in kinematic analyses are illustrated.

Table 1
Location of center of mass in supine position

Subject	Caudal to ASIS (cm)	Rostral to troch. Major (cm)
S1	1.3	16.0
S2	−0.6	13.7
S3	2.2	9.9
S4	2.2	21.8
S5	1.1	13.0
S6	12.8	−0.8
S7	4.2	5.6
S8	4.6	8.6
Avg	3.5	11.0
S.D.	3.9	6.4

did not overexert themselves or bang their heads against the support surface.

2.2. Force measurements

Two horizontal and four vertical force outputs were recorded from strain gauges mounted to four posts supporting a 182 × 70 cm aluminum plate (‘1’ in Fig. 1). These force outputs were then used, to calculate the net vertical reaction force and center of pressure (CoP).

The whole body CoG was calculated by dividing the subject’s total mass into 10 smaller masses, corresponding to the locations of 10 reflective markers fixed to the body for measuring kinematics (Fig. 1). The mass assigned to each marker was then estimated from a model of body mass distribution [29]. The CoG was calculated from:

$$CoG = \frac{\sum_{i=1}^{10} (x_i \cdot m_i)}{m_{total}}$$

where x_i represents the horizontal location of the ith marker and m_i the mass of that marker. For rigid segments, such as the thighs and calves, the mass was divided equally among the markers on the joints. For example, the mass assigned to the knee marker equaled the sum of one-half the mass of the thighs and one-half the mass of the calves. The markers on the trunk were assigned masses that distributed the weights of the shoulders, rib cage, abdomen, and arms. For the supine body position, the average location of the whole body CoG was 3.5 cm caudal to the anterior superior iliac spine (ASIS) of the pelvis and 11.0 cm rostral to the trochanter major (see Table 1). Prior to each experimental session, the force plate was calibrated statically with known weights and dynamically with a massive pendulum. During the experiment, the location of the CoP was determined with an accuracy of 3 mm and a precision <1 mm.

2.3. Kinematic measurements

Movement kinematics were measured with a trunk-contact device and a video-based motion analysis system. The trunk-contact device consisted of 101 bare-metal wires suspended by a metal frame 2 mm above the surface of the force plate (‘2’ in Fig. 1). The wires, separated by 5 mm each, were oriented from one side of the force plate to the other. A thin, cotton sheet covered the wires, insulating them from the subject’s skin. When the subject lay on the force table, the wires compressed and contacted the upper metal surface of the force table, creating an electrical short. The wires were connected to a 3-V battery source via a resistor network so that the voltage recorded across the circuit indicated the rostral-most wire in contact with the surface of the force table. The transverse tension exerted on each wire by the metal frame minimized the rostro-caudal movement of the wires.

At the beginning of each sit-up, the subject adopted the same body position relative to the contact device, ensuring that a minimum of one wire remained compressed by the time the subject completed the sit-up. For an average subject, the contact device measured body contact from $\approx$5 cm caudal to the acromion to the pelvis. Thus, there was a period from the sit-up onset until the shoulders were lifted that the only kinematic data available were from video-based motion analysis. The accuracy of measurement with the contact device was 5 mm, with an estimated precision of ±1 mm.

Video-based motion analysis was used to measure segmental kinematics in the sagittal plane (BTS, Milan). The precision of measurement depended on both the resolution of the motion analysis system ($\approx$1 mm) and skin slippage (estimated 3–14 mm). Ten passive reflective markers were adhered to the right side of the subject at the temple; nose; acromion; 8th, 10th, and 12th ribs; ASIS of the pelvis; trochanter major; lateral epicondyle; and lateral malleolus (Fig. 1). Two additional markers were fixed to the force plate 1.2 m apart in order to scale the motion analysis data, to establish the horizontal, and to locate the subject in the same initial position relative to the contact device for each sit-up.

As illustrated in Fig. 1, motion analysis data were used to calculate the inter-segmental angles between the head and shoulders (‘neck’), the thoracic and lumbar trunk (‘upper trunk’), the lumbar trunk and pelvis (‘lower trunk’), the pelvis with respect to the horizontal plane (‘pelvis’), and the thigh and the pelvis (‘hip’). ‘Total trunk angle’ was defined as the angle between the horizontal and a line connecting the shoulder and ASIS markers. ‘Total trunk angular velocity’ was the rate of change of the total trunk angle. ‘Pelvis angle’ was the angle between the horizontal and a line connecting the markers on the ASIS and trochanter major. Operationally, we defined ‘headward pelvic rotation’ as posterior motion of the rostral pelvis and anterior motion of the caudal pelvis. ‘Footward pelvic rotation’ was the opposite direction of motion (see Fig. 6). ‘Sit-up onset’ corresponded to the moment that an upward movement of the nose marker was first detected, and ‘sit-up offset’ corresponded to the moment that the total trunk angular velocity reached zero.

2.4. EMG recording

Contraction levels (EMG) were recorded (Noraxon) from eight muscles: sternocleidomastoideus (Ster), rectus abdominis (RecA), obliquus externus (EObl), pectineus (Pect), erector spinae (ESpi), tensor fascia latae (TenF), rectus femoris (RecF), and biceps femoris (BicF). The ESpi was inactive in most subjects, so the description of muscle activity in this paper is limited to the other seven muscles. Pairs of surface electrodes, 4 cm center-to-center, were applied over the belly of each muscle in parallel to the major orientation of muscle fibers. The signal was amplified (×5000) and band pass filtered (10–500 Hz). As all eight subjects were relatively lean, we could readily identify the appropriate sites of electrode application by having each subject perform a series of isometric contractions and palpating the skin over each muscle during the contractions. Each pair of electrodes was oriented in the primary direction of muscle fibers in the underlying muscle. The Pect is a relatively small muscle, so it is likely that the pair of electrodes over the Pect picked up activity from neighboring hip flexors.

2.5. Data acquisition and analysis

A data acquisition system (CED micro 1401) digitized six channels of force data at 500 samples/s and eight channels of EMG data at 2000 samples/s. The motion analysis system digitized 12 channels of reflective marker positions at 50 samples/s. The positions of the reflective markers were resolved into x- and z-components. The data were saved on disk if there were no missing or phantom markers. Otherwise, the sit-up was repeated.

All kinematic and EMG data were measured using automated programs written in IGOR (Wavemetrics). However, these measurements were screened for anomalous values, which were checked visually. During post-processing, the raw EMG signal was quantified by digital full-wave rectifying and low-pass filtering (f_c = 20 or 5 Hz). These EMG signals were averaged over intervals corresponding to kinematic events of interest.

To establish a functionally relevant gauge of contraction intensity and to permit comparisons among subjects, EMG measurements were normalized with respect to attempted maximal contraction levels. At the end of each experimental session, the subject lay supine and attempted three maximal contractions lasting 2–3 s each, from each of the six flexor muscles on the ventral body surface, and then in the prone position, from the erector spinae and biceps femoris. During these attempted maximal contractions, the subject was physically restrained by one of the experimenters in order to maintain isometric conditions. ‘Maximum contraction level’ was defined as the maximum EMG amplitude attained over the 3 contractions, as determined by a 100-ms moving average.

Contraction intensity was measured for each of five phases of the sit-up: (1) from sit-up onset to lumbar trunk lifting; (2) from lumbar trunk lifting to the onset of footward pelvic rotation; (3) from onset of footward pelvis rotation to the beginning of leg-lowering; (4) from onset of leg-lowering to leg-contact; and (5) from leg-contact to sit-up offset. The average EMG amplitude was calculated for each subject ($n = 8$), interval ($n = 5$), and muscle ($n = 8$). For the interval in which a muscle was recruited, the average amplitude of muscle contraction was based on the entire interval rather than on just the part of the interval during which the muscle was active.

3. Results

The sit-up appears to the eye as a single, fluid motion of the body axis (e.g. Fig. 2A), despite the large number of muscles recruited and joints moved. However, results indicate otherwise. Each stick figure in Fig. 2A illustrates the position of the body axis at a 100-ms interval for a representative sit-up. Shortly after sit-up onset, the total trunk angular velocity peaked (greater distance between the stick figures), then slowed to a minimum just before the mid-point (small distance between the stick figures), and then speeded up again before the end of the sit-up.

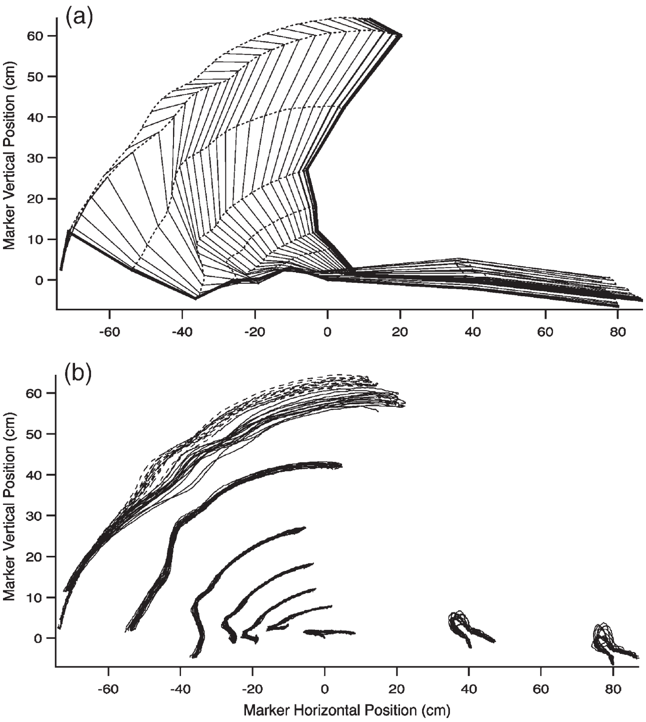

Fig. 2. Smoothness and repeatability of sit-up kinematics. In A, stick figures show the x- and y-positions of 10 reflective markers. Adjacent stick figures are separated in time by 20 ms. In B, reflective marker trajectories are superimposed for 15 successive sit-ups. The trajectories from the marker on the nose are dashed to distinguish them from those produced by the markers on the temple. In A, subject 7, sit-up 4; in B, subject 7, sit-ups 1–15.

For each subject, the kinematics were highly consistent from sit-up to sit-up, as shown for a representative subject in Fig. 2B. Each cluster of curves represents the 2-dimensional trajectory of a single reflective marker in 15 successive sit-ups. Though the variability in trajectory was small for all markers, it was smallest for those on the pelvis (3rd and 4th from the right) and greatest for those at the rostral- and caudal-most parts of the body axis. The traces in Fig. 2B, particularly those of the pelvis and legs, illustrate that body motion during a sit-up includes both rotation and translation. While kinematic variability was low for the 15 sit-ups obtained from each subject, there were some differences in kinematics among subjects, particularly in the height and pattern of leg movements (see Table 3).

3.1. Sit-up kinematics

In our study, the sit-up is described as having two relatively distinct parts, ‘trunk curling’ and ‘footward pelvic rotation.’ Trunk curling and footward pelvic rotation are readily distinguishable by the angular velocity of the trunk (Fig. 3A), which has two distinct peaks, separated by a local minimum about half-way through the sit-up. This bi-phasic pattern contrasts with the typical bell-shape velocity profile commonly seen for simple arm movements (e.g. Refs. [1,3]), such as in reaching or in pointing.

As illustrated by the total trunk angle in a representa-

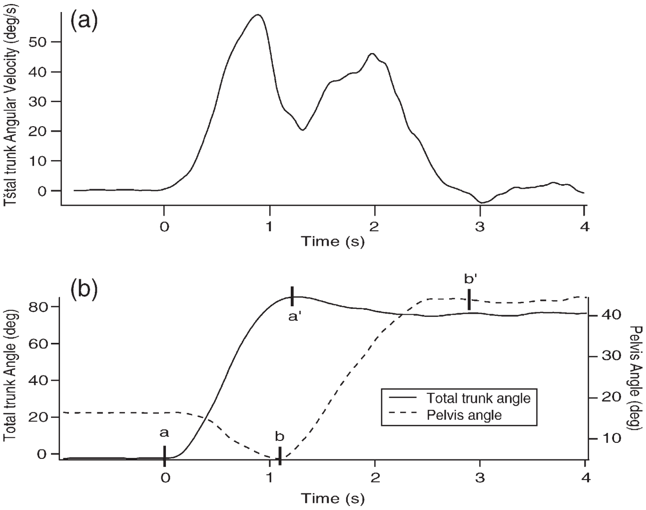

Fig. 3. Two components of the sit-up. In A, total trunk angular velocity is shown as a function of time. In B, the total trunk angle (solid line) and pelvis angle (dashed line) are shown with short vertical bars identifying (a) the onset of trunk curling, (b) the onset of footward pelvic rotation, (a’) the end of trunk curling, and (b’) the end of the sit-up. In A and B, subject 7, sit-up 4.

tive trial (solid line, Fig. 3B), trunk curling begins at sit-up onset a and ends at a', about 1.2 s into the sit-up. Footward pelvic rotation is illustrated by the pelvis angle (dashed line in Fig. 3B), beginning at b and ending with b'. During trunk curling, the pelvis rotates towards the head, rather than towards the feet (i.e. a–b), eliminating lordosis and flattening the lumbar trunk on the support surface. Trunk curling and footward pelvic rotation overlapped slightly (b–a') in all subjects (Table 2), but these two parts of the sit-up appear functionally distinct.

3.2. Sequential nature of the sit-up

The sequential nature of sit-up kinematics is illustrated in Fig. 4 for a representative sit-up. Fig. 4A shows three angles of the body axis involved in trunk curling: the neck angle (top), the upper-trunk angle (middle), and the lower-trunk angle (bottom). In this subject, the neck angle changed by only a few degrees during the sit-up. Some subjects flexed the neck early in the sit-up, and when weight was added to the head of the subject whose data are illustrated in Fig. 4, the neck flexed 15–20°.

In the representative sit-up illustrated in Fig. 4, the upper-trunk flexed ≈12 deg at the beginning of the sit-up. Most of this upper trunk flexion persisted through the end of the sit-up. After the first ≈0.5 s, the lower-trunk angle decreased, initially from headward pelvic rotation and loss of lordosis, and subsequently from lumbar trunk lifting. Thus, trunk curling consists of sequential upper-trunk flexion followed by lower-trunk flexion.

In the absence of any instruction to the contrary, all subjects lifted the legs from the support surface. Some subjects lifted the legs only slightly, and others lifted them more dramatically (Table 3), especially if the sit-up was challenging (see Fig. 7C). Leg height is shown as a function of time in Fig. 4C, with the knee in the upper trace and the ankle in the lower trace. In this trial, the knee and ankle were elevated more-or-less simultaneously, beginning within ≈200 ms of the start of the sit-up. The maximum elevation of the legs in this sit-up was 8 cm, reaching the zenith ≈1.2 s after the start of

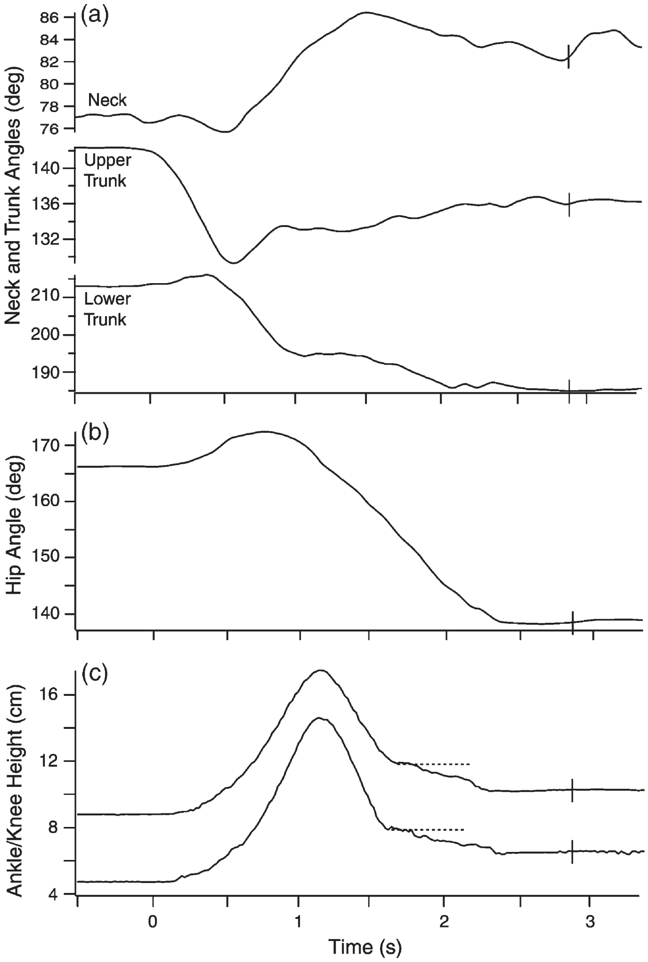

Fig. 4. Sequential nature of sit-up kinematics. In A, neck, upper trunk, and lower trunk angles are shown as a function of time. In B, hip angle is shown, and in C, knee (above) and foot (below) elevations are shown. Short vertical bars indicate the end of the sit-up. Horizontal dashed lines in C show leg contact with support surface. Subject 7, sit-up 4.

Table 2
Duration of sit-up phases—subject averages

Subject	Phase (s)	Phase 2 (s)	Phase 3 (s)	Phase 4 (s)	Phase 5 (s)	Total duration (s)
S1	0.61	0.32	0.47	0.42	1.12	2.94
S2	0.65	0.37	0.36	0.34	1.12	2.83
S3	0.65	0.32	0.10	0.56	0.58	2.29
S4	0.61	0.47	0.24	0.63	0.72	2.67
S5	0.59	0.39	0.32	0.18	1.25	2.73
S6	0.75	0.51	0.57	0.70	0.94	3.46
S7	0.77	0.42	0.28	0.51	0.95	2.93
S8	0.69	0.42	0.22	0.46	1.28	3.07
Avg	0.67	0.40	0.32	0.48	1.00	2.86
S.D.	0.07	0.07	0.15	0.17	0.25	0.36

Table 3
Peak knee elevation

Subject	Average knee elevation (cm)	S.D. (cm)
S1	4.1	1.4
S2	5.3	0.7
S3	4.3	0.6
S4	12.4	4.4
S5	3.6	0.6
S6	11.4	2.0
S7	7.3	0.9
S8	6.1	0.9
Avg	6.8	1.4
S.D.	3.1	1.2

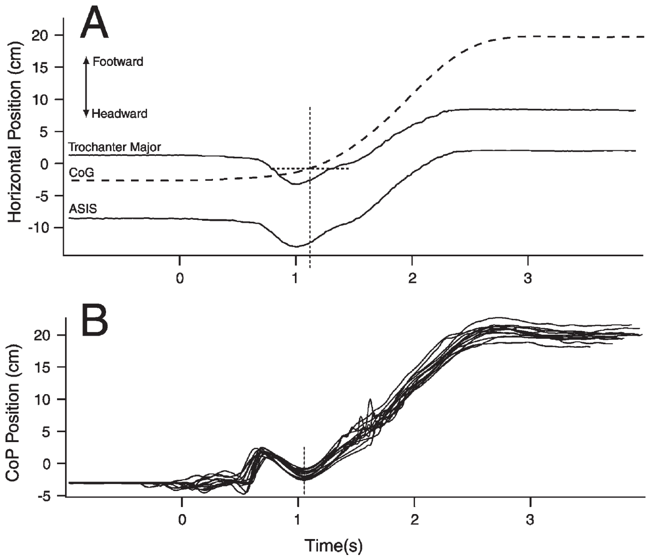

Fig. 5. Motion of center of gravity and center of pressure. In A, the horizontal location of the CoM is plotted with the horizontal locations of the ASIS and trochanter major reflective markers. The onset of footward pelvic rotation is indicated by the vertical dashed line, and the simultaneous CoG location by the horizontal dashed line. Note footward direction is up. In B, the CoP records from 15 successive sit-ups are superimposed and are aligned on the end of the torque transient that began at ≈0.6 s (vertical dashed line). In A, subject 7, sit-up 4. In B, subject 7, sit-ups 1–15.

the sit-up. About half of the subjects lifted the knees from the table before the feet, with passive knee-flexion pulling the feet towards the pelvis. Finally, knee-extensor activity locked the knees, resulting in foot elevation. The other half of the subjects lifted the legs as a single unit. With respect to muscle activity, the principal difference between these two groups of subjects was the timing of knee-extensor activity.

Hip angle (Fig. 4B) roughly paralleled pelvis angle (i.e. Fig. 3B), initially extending by several degrees and then flexing after ≈0.7 s. During the latter part of this sit-up, the legs were lowered towards the support surface, contacting it at ≈1.6 s in the sit-up illustrated in Fig. 4C. Contact with the support surface produced a ‘shoulder’ in the leg height traces (horizontal dashed lines in Fig. 4C). The slow descent of the knee and ankle markers following foot contact was caused by knee extension and ankle eversion, respectively. Ankle inversion/eversion was observed visually in all subjects, but not recorded.

3.3. Motion of the center of gravity relative to the pelvis

In the sit-up, one of the purposes of trunk curling is to shift the CoG towards the feet so that the trunk and pelvis can rotate towards the feet. By decreasing the static torque on the upper body and by increasing the static torque on the lower body, trunk curling allows the hip flexors to lift the trunk and head into a sitting position rather than to lift the legs. Fig. 5A shows, for a single sit-up from a representative subject, the motion of the CoG during a sit-up. When supine, this subject’s CoG was located approximately mid-way between the ASIS and the trochanter major. The crossed, dashed lines indicate the time the pelvis began to rotate towards the feet (footward pelvic rotation). Fig. 5A shows that the CoG had moved to a point 2 cm caudal of the trochanter major by the time of the onset of footward pelvic rotation, partly as a result of headward pelvic rotation and partly due to a caudal shift in the CoG.

3.4. Dynamics

While dynamics may play a significant role in sitting-up, the CoP records from sit-ups performed with a 3-s duration suggest that dynamics do not, at least, dominate this type of sit-up. The principal difference between the CoG (Fig. 5A) and CoP (Fig. 5B) rests in a modest force transient that occurs ≈0.7–1.0 s after the onset of the sit-up, which corresponds to the time the lumbar trunk is lifted from the support surface. In Fig. 5B, the CoP trajectories of all 15 trials from a single subject are superimposed and horizontally aligned arbitrarily, on a local minimum ≈1 s after the onset of the sit-up (vertical dashed line). Much of the residual variability in the CoP trajectories can be attributed to small differences in the durations of the sit-ups (i.e. horizontal variability), rather than in the amplitudes of surface reaction forces (i.e. vertical variability).

3.5. Phases of the sit-up

In addition to the trunk curling and footward pelvic rotation components of the sit-up, the sit-up can be further subdivided into 5 sequential phases, as shown in

Fig. 6A. Phase I and II comprise trunk curling, beginning with head and upper-trunk curling, followed by lower-trunk curling, respectively. The transition from phase I to II is the time point at which the velocity of the reflective marker on the 12th rib reverses direction from downward (i.e. during headward pelvic rotation) to upward (i.e. during lumbar trunk lifting). The last three phases of the sit-up comprise footward pelvic rotation and are distinguished by the relative motion of the hips, legs, and pelvis. Phase III is a relatively brief period during which time the pelvis begins to rotate towards the feet (footward pelvic rotation), but the legs continue to lift because of active hip flexion. The transition from phase III to IV is defined by the onset of leg lowering, and the transition from phase IV to V, as the moment of leg contact with the support surface. Phase V ends when trunk angular velocity reaches zero.

A more detailed view of pelvic motion during the sit-up shown in Fig. 6A is illustrated in Fig. 6B. The pelvis rotated towards the head in phases I and II with horizontal translation. At the beginning of phase III, the pelvis motion reversed direction towards the feet, but it did not retrace its original trajectory, rising higher off the support surface during footward pelvic rotation, perhaps a result of gluteal contraction. During phase III, trunk curling and footward pelvic rotation overlapped, and contact with the support surface decreased to a small region under the pelvis, with the trunk and legs folding up onto the pelvis. Phases III and IV were distinguished as the only ones in which propulsion toward the feet was completely passive. Hip flexion during phase IV (e.g. Fig. 4B) served to delay foot contact the support surface. In phase V, which comprised the final ≈50% of footward pelvic rotation, propulsion was produced actively by hip flexor contraction. The timing of the five phases of sitting up is shown for all eight subjects in Table 2. While leg motion was relatively consistent for each subject, the height of leg lift varied considerably from subject to subject (Table 3).

3.6. The ‘critical period’ of sitting up

Phase II, the period of lumbar trunk lifting, represents a critical period of the sit-up, when the maximum load must be lifted. In the process leading up to lumbar trunk lifting, the head and trunk are gradually ‘peeled’ from the support surface, as shown by a recording from the table contact device in Fig. 7A. The rostral-most contact

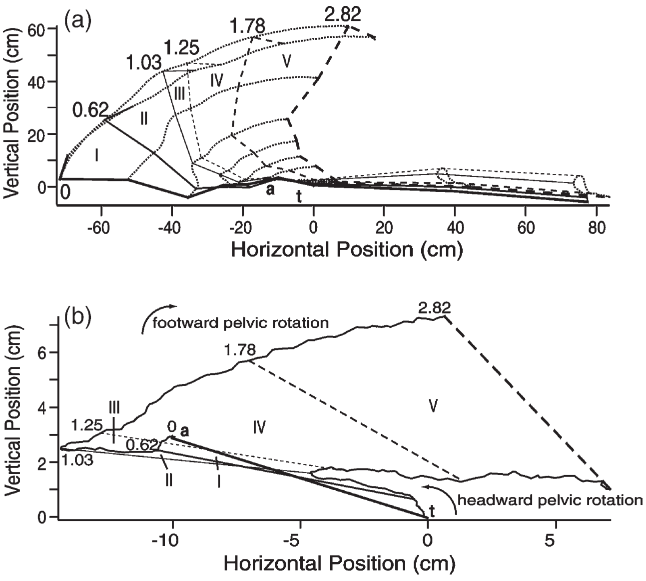

Fig. 6. Five phases of the sit-up. In A, the stick figures are shown at transition times (in seconds) from one phase to the next. In B, marker positions are shown for the ASIS and the trochanter major at each phase transition time. In A and B, ‘a’ refers to the ASIS reflective marker, and ‘t’ refers to the marker on the trochanter major. Subject 7, sit-up 4. Phase numbers are indicated by Roman numerals.

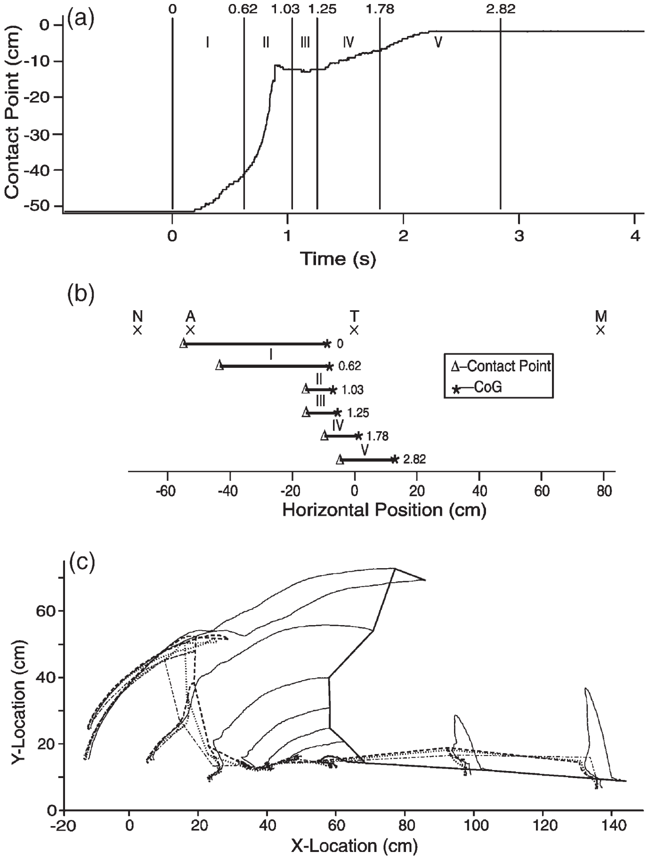

Fig. 7. Critical point of the sit-up. In A, the motion of trunk axis of rotation is illustrated by output from the contact device. Note the rapid motion of the contact point during phase 2 (i.e. between 0.62 and 1.03 s). In B, the horizontal positions of the trunk contact point (Δ) and the CoG (∗) are shown at the beginning of each phase and at the end of the sit-up. The horizontal positions of the nose (N), acromion (A), trochanter major (T), and external malleolus (M) are shown for the supine subject at the top (Xs). In C, the positions of the 10 reflective markers on the subject’s body are shown for 3 sit-up failures (dotted and dashed lines) and the first successful sit-up (solid lines) when weight was added to the head. Note the large leg-lift in the successful sit-up. In A and B, phase numbers are indicated by Roman numerals. Subject 7—in A and B, sit-up 4.

point during trunk curling corresponded roughly to the instantaneous axis of trunk flexion, at least in the horizontal plane. Thus, the instantaneous axis of trunk flexion translated caudally during phase I at ≈25 cm/s, but in phase II, the speed of axis translation increased to ≈200 cm/s, as the lumbar trunk was lifted as a quasi-rigid segment. Once the lumbar trunk was lifted, forward motion paused for several tenths of a second during a period termed the ‘critical period’ (≈0.9–1.1 s in Fig. 7A).

The stability of an individual while sitting up depends on maintaining adequate separation between the trunk axis of rotation and the CoG, because the magnitude of separation influences the static torque on the portion of the body that remains in contact with the support surface. The greater the static torque on the body in contact with the support surface, the better the leverage on the part of the body being lifted. Fig. 7B shows the relative locations of the contact point and the CoG during a representative sit-up. Initially, the separation between the contact point and CoG was ≈50 cm, but by the end of phase II, the contact point had moved caudally >40 cm while the CoG moved only a few centimeters, reducing their separation to <10 cm. This dramatic reduction in the separation of the CoG and the trunk axis of rotation makes phase II a critical period of the sit-up.

The records in Fig. 7C illustrate three successive sit-up failures in a subject with weight added to the head, followed by a successful sit-up. A comparison of the body position during these failures with the corresponding stick figures in Fig. 6A reveals that the failures occurred during phase II, when the reflective marker on the 8th rib followed a distinctive ‘S’-shaped trajectory. The existence of a critical point in phase II is not surprising because it is during this phase that the weight of the head and entire trunk must be lifted at the same time that the trunk contact point approaches the CoG.

3.7. Pattern of muscle activity

Consistent with the kinematics of the sit-up, the pattern of muscle activity was complex, with the pattern exhibiting both serial and parallel components. The EMG signals from a sit-up are displayed in Fig. 8 for the seven muscles, the activity of which was recorded and found to change over time. The amplitude of muscle activity was normalized to attempted maximal levels, showing that the abdominal flexors reached 80% of maximum intensity during a normal sit-up. The hip flexors were also modulated to relatively high levels, between 40–50% of attempted maximum. The onset of muscle activity and the timing of peak activity had the appearance of a distal to central sequence (i.e. rostral and caudal, to pelvis, respectively). Some muscles, such as the abdominal flexors, had single-peak responses,

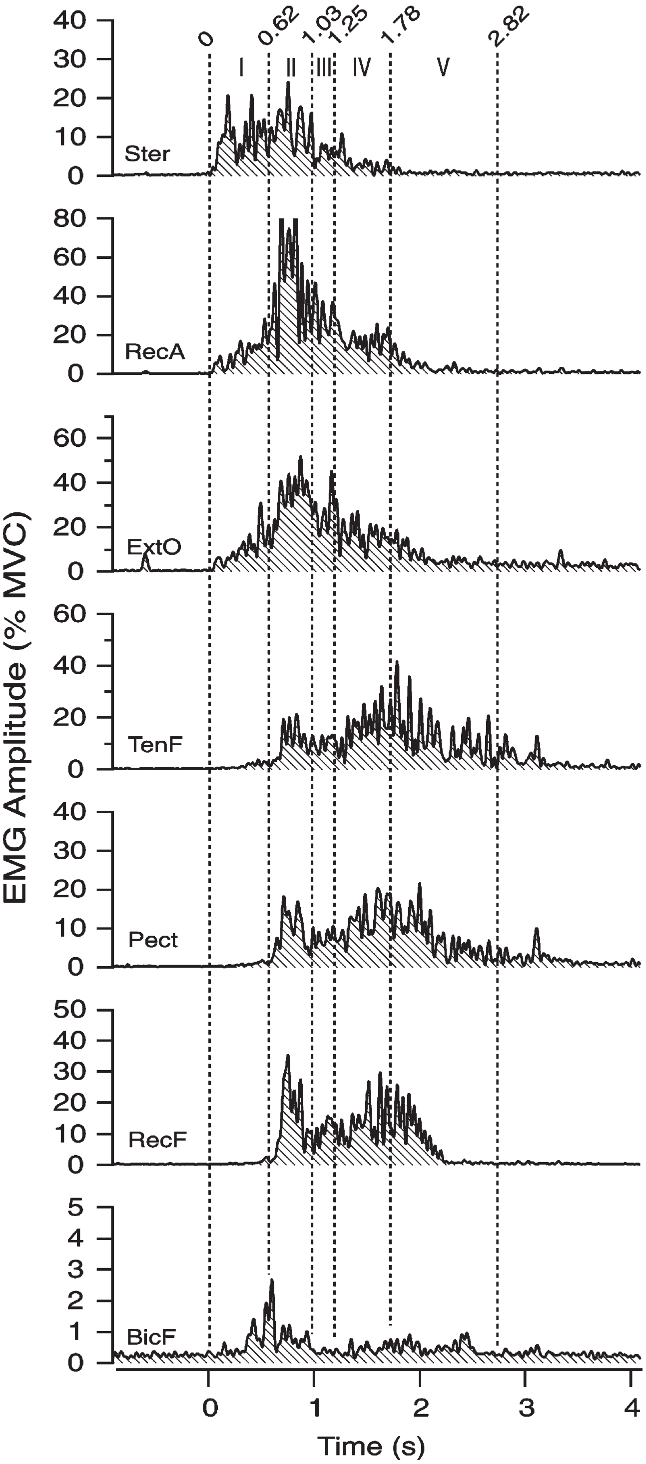

Fig. 8. EMG activity during a sit-up. Rectified, EMG recordings (f_c = 20 Hz) are shown from top to bottom: sternocleidomastoideus (Ster), rectus abdominis (RecA), external obliquus (ExtO), tensor fascia latae (TenF), pectineus (Pect), rectus femoris (RecF), and biceps femoris (BicF). The EMG amplitudes are given in terms of percent of attempted voluntary maximum contractions. Phase numbers are indicated by Roman numerals. Subject 7, sit-up 4.

whereas the hip flexors peaked during phase II and then again during the transition from phase III to IV.

In contrast to the kinematics and dynamics of sitting up, muscle activity was relatively variable from trial to trial, even in the same subject. As shown in Fig. 9 for 15 trials from a single subject, the onset time, peak activity, offset, and the overall pattern of activity clearly differed for different trials. The top trace in each panel of Fig. 9 depicts the average pattern of muscle activity, clearly demonstrating a different pattern and timing of activity, on average, for the Ster, RecA, and RecF.

During each phase of the sit-up, the relative contributions of the seven muscles differed. In each bar graph in Fig. 10, the EMG amplitude of each muscle was scaled as a percentage of the amplitude during the phase of peak activity (i.e. 100%). The height of each bar represents the grand mean percent of contraction for all eight subjects. Each bar graph illustrates the relative

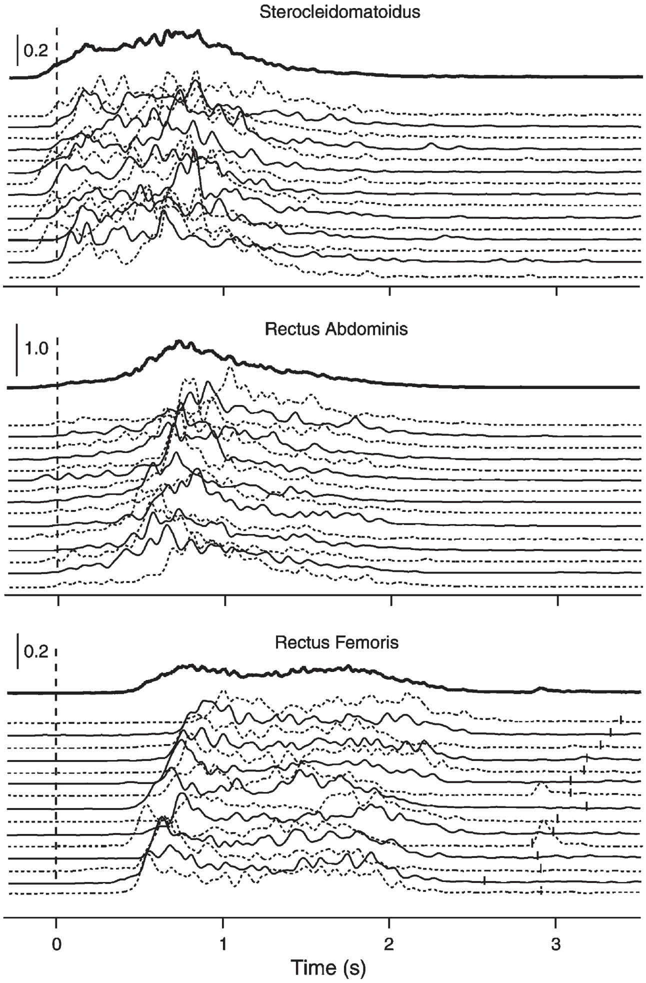

Fig. 9. Different EMG patterns and variability of muscle activity. Rectified and smoothed (f_c = 5 Hz) recordings of muscle activity are superimposed for 15 successive trials. Traces have been aligned with respect to sit-up onset and vertically shifted. The ends of the sit-ups are shown by vertical bars in rectus femoris records. Calibration bars in mV. Subject 7.

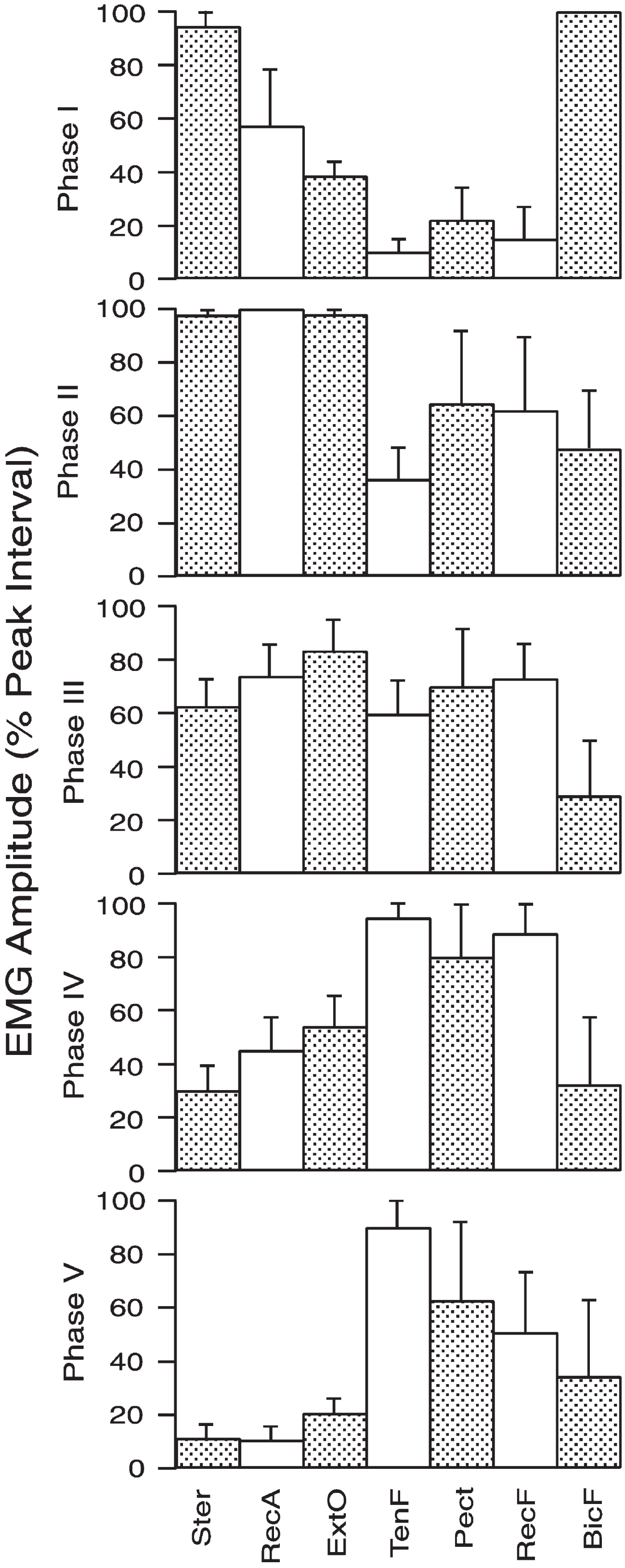

Fig. 10. Relative contributions of muscles during each of the five sit-up phases. The ranking of the contribution of each muscle is represented by a bar in each epoch (n = 8). A value of 100 was assigned for the interval with peak activity, and activity in the other intervals was relatively scaled. ANOVA showed a significant effect of the phase on the ranking of muscle activity for all 8 muscles ($p < 0.0001$). Grand means ±S.D. of all eight subjects.

amplitudes of the seven muscles for a particular phase of the sit-up. In the bar graph representing activity during phase I, peak activity occurred in Ster and BicF. In phase II, peak activity occurred in Ster, RecA, and ExtO. In phase III, most muscles were active at about 60% of maximum. In phase IV, peak activity occurred in the three hip flexors, TenF, Pect, and RecF, and in phase V, TenF remained at near peak amplitude while activity declined in the other two hip flexors.

4. Discussion

The study presented in this paper represents an initial investigation into how the human CNS coordinates voluntary movements that are biomechanically complex, a characteristic of many natural voluntary movements. We have argued, primarily on theoretical grounds, that there may exist many aspects of motor coordination that might only be revealed in complex movements [16]. The purpose of this study was to analyze the kinematics and EMG activity associated with sit-ups in order to identify what part of this biomechanically complex movement might yield, under closer examination, new insights into how the CNS coordinates movement.

The sit-up was used as a behavioral model for several other reasons. This movement involves the voluntary control of the body axis, which is commonly impaired in neurological disorders affecting coordination and balance, but which has not been well-studied. In addition, the sit-up involves the generation of relatively large active forces, whereas previous studies of voluntary movements have been largely limited to those involving small forces. The form of sit-up used in this study—with the legs straight and unconstrained, the arms folded across the chest, and a 3-s movement time—was designed to optimize consistency in kinematics between and within subjects.

4.1. Subdivision of the sit-up

We subdivided the sit-up kinematically, hypothesizing that movement of distinct parts of the body, and localized movements performed at different times, might be discretely controlled by the CNS. A three-component model of the body comprising the head/trunk, pelvis, and legs was used to decompose the sit-up into the five kinematic phases described in Figs 6 and 7. The principal observation provided by this decomposition was that the sit-up, while subjectively appearing to be one, fluid motion (e.g. Fig. 2A), is actually a two-part movement. The biphasic appearance of total trunk angular velocity (e.g. Fig. 3A) is consistent with the conclusion that the sit-up consists of two serially arranged components: trunk curling and footward pelvic rotation. Trunk curling includes phases I and II, and footward pelvic rotation includes phases III–V. The biphasic property the sit-up is also evident in the rotation of the pelvis, which rotates towards the head during phases I and II and then reverses direction during phases III–V (Fig. 3). The reversal in direction coincides in time with the minimum in whole trunk angular velocity.

Headward rotation of the pelvis in phases I and II might be critical to successful sit-ups (e.g. Fig. 3B). Headward pelvic rotation flattens the lumbar trunk on the support surface, allowing a reaction force to be produced during the lumbar trunk lift (see Fig. 5B). Headward pelvic rotation may serve several additional functions. First, it increases the extent of the lower body that is lifted from the support surface by leg elevation, which increases the static torque on the lower body. Second, headward pelvic rotation shifts the pelvic contact point on the support surface towards the head at the same time that trunk curling shifts the CoG towards the feet, resulting in an earlier cross-over between the CoG and pelvic contact point (Fig. 5A). The pelvic contact point or, more precisely, the point of highest pressure, effectively represents the axis of rotation between the pelvis and the support surface. Third, headward pelvic rotation may reconfigure the lumbo-sacral spine in order to increase the psoas major moment arm, leading to greater flexion torque on the trunk.

While relatively high levels of muscle activity are generated to produce trunk curling, the rotation of the pelvis and upper body during footward pelvic rotation is largely passive, taking advantage of gravitational pull on the lower body in order to rotate the pelvis and upper body into a sitting position. During phases III and IV, the pelvis and trunk rotate toward the feet, with the pelvis converting rotational motion into horizontal translation, much like the action of a wagon wheel. While the motion during phases III and IV is largely passive, hip flexor contraction reaches a maximum at this time, delaying leg contact with the support surface and, thereby, making maximum use of gravity. Hip flexor activity continues into phase V, to actively lift the trunk into its final position.

Between phase I and phase IV of the sit-up, the legs are lifted from the support surface. To mobilize static torque on the lower body, the legs only need to be unweighted, so it is unclear why they are lifted completely off the surface, occasionally by >20 cm. The presence of hip and knee flexor activity suggests that leg-lifting is active, rather than entirely passive due to passive elastic forces generated by the pelvis on the femur during headward pelvic rotation. The height of the leg-lift was the one feature of the sit-up that differed considerably across subjects (see Table 3), but the reasons for this variance are unclear. As previously mentioned, leg-lifting during phases III and IV may be useful because it prolongs the period of passive pelvic rotation towards the feet. However, the higher the leg lift, the less static torque on the lower body, making it difficult to explain why challenging sit-ups (e.g. the successful sit-up in Fig. 7C) are associated with even higher leg lifts than are normal sit-ups. Two possibilities are that lifting the legs might increase the moment arm of psoas major on the femur or that deceleration of the legs at the peak of the leg-lift might transfer momentum through the pelvis to the lumbar trunk. These hypotheses require additional systematic testing, in conjunction with biomechanical modeling.

4.2. Motion of the CoG

Because of body-weight distribution in the supine position (see Table 1), the CoG must shift toward the feet for the sit-up to take place. This shift of CoG is the primary function of trunk curling, and it must be accomplished without allowing the trunk contact point to approach too closely to the CoG (Fig. 7B), which would create an unstable posture and potentially lead to a sit-up failure. Similarly, the sit-to-stand maneuver involves first shifting the whole body CoG forward over the feet, prior to leg extension and rising [35,36,38]. Thus, the sit-up and the sit-to-stand maneuver belong to a class of voluntary motor activities that involve two distinct tasks: first, to shift the CoG and second, to change the posture. Movements involving anticipatory postural adjustments also belong to this two-part class of movements, as the anticipatory adjustment shifts the whole body CoG [7,9,12] or even just the CoG of a single extremity [24], to prevent equilibrium from being disturbed. Forward and backward trunk-bending from a standing posture also involves compensatory shifts in the CoG [4,17,31,32], although in these maneuvers, the two parts of the movement are executed in parallel, rather than serially. The purposive shift of CoG in such movements involves a high level of coordination, since degeneration of the cerebellum, a brain structure long known to be involved in coordination (e.g. Ref. [6]; see also Refs. [2,18,33], renders individuals incapable of performing sit-ups and trunk-bending [6].

One of the goals of this study was to measure when, during the sit-up, the whole body CoG crosses over the ‘contact point’ of the pelvis with the support surface. In relatively slow sit-ups as in this study, which are not likely to involve large dynamics, this cross-over should coincide with the onset of footward pelvic rotation and hip flexor activity. We hypothesize that the CNS monitors a proprioceptively generated construct of CoG in order to trigger hip flexor activity and other active events associated with footward pelvic rotation. Vibration of the erector spinae, which stimulates muscle spindle afferents [10,11], was previously shown to disrupt the execution of the sit-up [14], suggesting such a sensory triggering mechanism. Because of technical limitations of the study presented here, we were unable to measure precisely the location of the pelvic contact point and, therefore, to determine the cross-over time of the CoG and the pelvic contact point (Fig. 5A). Future studies will employ a force-sensor array to measure the pelvic contact point with the support surface.

4.3. Critical point of the sit-up

Most individuals can efficiently perform the kind of sit-up used in this study without the benefit of practice, as the sit-up is a natural movement. However, because such large forces are required to lift the head and trunk during the sit-up, and because this lifting must be precisely coordinated with pelvic motion, inappropriate timing or intensity of muscle activation can cause the movement to fail completely. Based on results from screening potential subjects for our study, we observed that approximately 5% of ‘normal’ individuals lack the ability to perform a sit-up, despite a relatively normal body mass distribution and adequate strength. Apparently, coordination in a sit-up must be precise, with a level of precision in excess of the capability of a small, but significant, fraction of normal individuals.

Based on our kinematic analysis, the requirement for precise coordination may predominate during the trunk curling part of the sit-up. This predominance is suggested by the occurrence of a critical period during phase II and, in contrast, by the largely passive motion of the body during phases III and IV. During trunk curling, coordination of the CoG with both the trunk contact point and pelvic rotation might play a critical role in a successful sit-up.

In terms of coordination, lumbar trunk lifting during phase II represents the most critical part of the sit-up because the weight that is lifted is the greatest during the sit-up, and the separation of the CoG and trunk axis of rotation reaches a minimum just after lumbar trunk lifting (Fig. 7B). The body position achieved during lumbar trunk lifting is quite unstable because contact of the entire body with the support surface is reduced to just a small portion of the pelvis, and the total trunk angular velocity slows to a minimum. Thus, not surprisingly, sit-ups usually fail due to added weight (Fig. 7C), fatigue, or lack of coordination, during the lumbar trunk lift. To assist with the lumbar trunk lift, a reaction force may be produced (Fig. 5B) to accelerate the lumbar trunk upwards. More detailed analyses of the pressure distribution under the lumbar trunk and the curvature of the spine might clarify, in future studies, the role of this hypothesized lumbar reaction force, as well as the relationship between the trunk contact point and the CoG. It is clear, however, that the sudden jump of the trunk contact point in Phase II to a point <10 cm rostral to the CoG (e.g. Fig. 7A and B) makes the individual performing a sit-up momentarily unstable.

4.4. Temporal pattern of muscle control

The spatial and temporal patterns of muscle activity provide clues to the strategies the CNS uses to control movements. However, most previous studies of axial movements, such as trunk-bending during standing (e.g. [4,32]), weight-lifting (e.g. [37]), the sit-to-stand maneuver [35,36,38], and sit-ups (e.g. [5,20–22,25–28,30,34] have provided much more insight into strategies of exercise or injury-prevention than into the coordination of these movements. A number of sit-up studies have included electromyographic recordings (e.g. [5,19–22,25,34]), but these studies have focused more on the level of muscle activity than timing (see however, Refs [17,32] for trunk-bending).

A fundamental property of motor control is the temporal pattern of coordination imposed by the CNS. In simple movements that involve just a few joints, control is typically carried out in parallel, with a synchronous onset and offset of motion and muscle activity. Pointing, which can involve as many as five joints of the arm and hand, and more than 10 degrees of freedom, is controlled in parallel. More complex movements, such as reaching-and-grasping, throwing, and locomotion, appear to involve serial as well as parallel control. Serial control is, in some ways, more complex than parallel control because it requires that serial components of the overall movement be coordinated temporal as well as spatially. Similarly, involvement of feedback in serial and parallel control may be fundamentally different (e.g. [13]). Our previous observation that muscle vibration can disrupt the sit-up indicates that feedback control does take place in sit-ups [14]. Feedback control is also suggested by the variability of EMG activity in sit-ups (Fig. 9), for it seems unlikely that successful sit-ups could be reliably produced by an open-loop motor program with this degree of variability.

The pattern of muscle activity observed in sit-ups was particularly complex, exhibiting both serial and parallel characteristics (e.g. Fig. 8). In general, muscle activity proceeded peripherally (i.e. legs and neck) to centrally (i.e. pelvis), suggesting that a high degree of control is exerted over pelvic motion during the sit-up. Consistent with this hypothesis, the variability of pelvic kinematics was lower than any other part of the body during the sit-up (Fig. 2B).

Our analysis of muscle activity in individual muscles (i.e. Fig. 10) indicates that different muscles are responsible for executing different sub-tasks of the sit-up (e.g. trunk-curling, hip flexion). Conversely, individual muscles may serve different functions at different times during the sit-up. For example, the hip flexors stabilize the pelvis during abdominal contraction (phases I and II), then delay leg contact with the support surface (phases III and IV), and finally rotate the pelvis and trunk into the final position (phase V). A qualitative comparison of Ster, RecA, and RecF (Fig. 9) revealed a striking difference in the activation patterns of these three muscles, in terms of onset, peak, and offset timing as well as the shape of the intensity–time relationship.

The specific roles of the biceps femoris, and the psoas major from which we did not record, merit additional discussion. Psoas, a major muscle of the pelvis, is inaccessible to surface recording, although it is possible to record intramuscularly with wire electrodes (e.g. [23]). Psoas major almost certainly influences trunk curling during lumbar trunk-lifting, due to its anatomical arrangement and size. It seems unlikely that the control of pelvic and trunk motion during the sit-up can be adequately understood without also characterizing the activity of psoas major (cf. [5]).

The function of biceps femoris activity is also unclear, even though this muscle produces a clear and repeatable burst during phase I. The long head of biceps femoris is bi-articular, with a proximal attachment near the ischial tuberosity of the pelvis and a distal attachment on the tibia. One possible function of biceps femoris activity is to assist in headward pelvic rotation. However, the amplitude of the biceps femoris burst is typically $<10\%$ of maximum and relatively brief, so this burst might originate from local reflexes that play no functional role in the sit-up (e.g. [16,39,40]).

Our analysis of muscle activity suggests that the CNS uses both serial and parallel control mechanisms to coordinate the sit-up. In simpler movements, serial control as well as some types of parallel control might not be evident, thus limiting our understanding of control mechanisms used to coordinate voluntary movement. In the study presented here, we provide a starting point for more detailed analyses of axial movements, focusing on different kinds of control mechanisms and functions that muscles might serve in natural, biomechanically complex movements.

Acknowledgements

The authors gratefully acknowledge Graham Kerr, Ph.D. and Ron Jacobs, Ph.D. for their contributions to the development of the force table and to the National Institutes of Health for funding this project (AR31017, AR46007). S.V. was supported by the Fund for Scientific Research, Flanders, Belgium. S.B. was supported by the Research Council of the Katholieke Universiteit Leuven.

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