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ANALYSIS OF STANDING UP AND SITTING DOWN IN HUMANS: DEFINITIONS AND NORMATIVE DATA PRESENTATION

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Abstract—A formal definition of human standing up and sitting down movements based on sagittal plane goniometric and force plate data from 20 normal subjects is presented. This definition is comparable to the established gait cycle diagram, and consists of defined characteristic events and relative time intervals between them. The characteristic events are selected primarily on changes in ground reaction forces.

The terminology proposed may be valuable for introducing more formalized and standardized reporting of both qualitative and quantitative studies in both normals and in patients. This presentation is directed toward the process of defining generally acceptable standards for human standing up and sitting down movements.

NOMENCLATURE

BW	body weight
GRV	ground reaction vector
ST	stand position
pp	peak to peak value
x, y, z	global coordinate system axes
ϕ_a	ankle angle
ϕ_k	knee angle
ϕ_h	hip angle
y_c	anterior–posterior displacement of GRV
F_x, F_y, F_z	components of GRV force
M_x, M_y, M_z	components of GRV moment
$t_{u0}, t_{u1}, t_{u2}, t_{u3}, t_{u4}, t_{u5}$	standing up event times (marker times)
$t_{d0}, t_{d1}, t_{d2}, t_{d3}, t_{d4}, t_{d5}$	sitting down event times (marker times)
dF_y/dt	time derivative of F_y
dF_z/dt	time derivative of F_z
t	T-test t value
df	T-test degrees of freedom
p	T-test 2-tail probability
s	seconds

INTRODUCTION

The terminology and biomechanics of normal and pathologic gait are rather well defined and accepted. This has been achieved by a number of gait labs (Murray, 1967; Inman *et al.*, 1981). The well-known gait cycle diagram provides a biomechanical definition which has been invaluable to researchers in standardizing and formalizing the reporting of research findings in the field of gait analysis (Murray, 1967; Winter, 1987).

In contrast to the biomechanical elaboration of gait, the essential functions of standing up and sitting down are not well standardized or uniformly defined (Burdett *et al.*, 1985; Bajd *et al.*, 1982; Yoshida *et al.*, 1983; Ellis *et al.*, 1984; Murray *et al.*, 1967; Kelley *et al.*, 1976; Andersson *et al.*, 1986). Most previous studies concentrated on obtaining moments at hip, knee or ankle joints to determine the time course and find the maximum values. Other studies have described how body segments move. A detailed definition of the processes of standing up and sitting down, comparable to the definition of the gait cycle (Murray, 1967; Winter, 1987) has not yet been proposed. The purpose of this paper is to provide normative data and analyze the act of standing up from a seated position and sitting down from a standing position. The aim is also to describe and propose definitions with terminology for defining phases of standing up and sitting down, and define events, quantities for best events detections and specific time of occurrence, so that the detection and separation of phases can be formalized. In this paper standing up and sitting down were studied in normal individuals.

The functions of standing up, standing, and sitting down are important in man. They are physiologically essential functions and prerequisites for gait (Ragnarsson *et al.*, 1981; Igaroski and Black, 1985; Paulus *et al.*, 1984). Many everyday activities are performed while standing, and this posture is vital for proper function of many organs (e.g. kidney, bladder and intestines) (Leo, 1985; Krebs *et al.*, 1983; Comar, 1955; Gould *et al.*, 1955). In-patients who are predominantly wheelchair users for at least several hours of standing per day are thought to be of special importance. This not only assists the above-mentioned functions, but also may help maintain proper bone loading and prevent excessive bone demineralization (Leo, 1985; Aloja *et*

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al., 1978; Lukert, 1982). Skin pressure relief is thought to be an additional benefit of standing.

The motivation for performing this study arose from a desire to improve application of FES technology for these functions in the disabled population. Functional electrical stimulation (FES) of upper motor neuron paralyzed muscles in spinal cord injured and other patients (stroke, cerebral palsy, and head injury) can provide active forces to assist standing up, stance, and sitting down in these patients (Kralj *et al.*, 1973; Bajd *et al.*, 1982; Quintern and Jaeger, 1987). FES enabled standing and reciprocal gait restoration in spinal cord injured patients (SCI) is an emerging technology, with reasonable potential for substantial future advances in rehabilitation. In spite of the fact that the feasibility for FES enabled standing up, standing, reciprocal gait and sitting down was proven (Kralj *et al.*, 1973; Marsolais *et al.*, 1983; Kralj and Bajd, 1989), the field does not progress according to expectations, mainly due to the lack of biomechanical formal knowledge related to the question of how these movements are synthesized by neural control in man. Therefore analysis and formal definitions of biomechanical events are the first steps toward the solution of the posed problem. From a functional and biomechanical point of view, there are many studies available on normal and pathological gait, and gait obtained by means of FES (Kralj *et al.*, 1973; Maležič *et al.*, 1984; Marsolais *et al.*, 1983). However, only scant biomechanical data for standing up and sitting down exist. The proposed terminology would presumably be useful in other areas of research involving human biomechanics of standing up, standing and sitting down like in rehabilitation, ergonomics, sports medicine, etc.

METHODS

Subjects

Twenty normal subjects were chosen to participate in this study, 15 male and 5 female. The subjects had no known neurological or orthopaedic problems. Body segment parameters were measured for each subject. The age, sex and segment lengths for all subjects are summarized in Table 1. The average characteristics of the population are also given. The maximal, minimal and average values and the standard deviations for the length/height data of all subjects are presented in Fig. 1.

Shank length was measured from 0.5 cm anterior and 1 cm above the medial malleolus to the visually determined approximate knee center of rotation, thigh length was measured from the knee center of rotation to the great trochanter, and trunk length from the greater trochanter to the center of shoulder glenohumeral rotation measured in the neutral position. The height of the medial malleolus and the length of the shoe were also assessed. Tiny reflective markers for photography were placed on the left side in all above-mentioned centers of rotation. Knee, hip and shoulder length/height were calculated in Table 1.

Equipment

The block diagram of the experimental set-up is shown in Fig. 2, and the description for each block is presented below.

Biomechanics platform. A commercially available force plate using strain gauge transducers (AMTI model 0R6-5-1) was used to record the ground reaction forces in this study. The coordinate system for standing up/sitting down was selected in accordance with the AMTI force plate coordinate system. Three orthogonal forces, F_x, F_y, and F_z (lateral shear, anterio–posterior shear, and vertical respectively) were measured. Three orthogonal moments, M_x, M_y, and M_z, were also recorded. In normals, because of the ability to move symmetrically, the F_x force and M_z and M_y torques are small, while in patients this may not be the case.

To calculate the anterio–posterior point of application of the net ground reaction vector (GRV) displacement (along the *y*-axis), M_x and F_z were used as shown in equation (1).

$$y_c = M_x/F_z. \qquad (1)$$

Goniometric system. A clinical goniometric system (MIE Medical Research, Ltd, Gait Analysis System) was used to measure the movements of the hip, knee, and ankle joints on the right-hand side. This device is an exoskeleton type goniometer system. It provides a ± 5 V analog signal proportional to joint angle. Goniometers were carefully placed on the right-hand side of the subject and photographic markers on the left-hand side. By means of photographic records and placed plumb lines, verification of goniometric recorded data was ensured. The photographically obtained enlarged pictures served for intermittent verification and possible recalibration of goniometrically obtained records.

Data acquisition system. A computer (IBM PC/XT) was used to collect data in real time, with a 16 channel 12 bit A/D board (Tecmar Labmaster). Analog data were sampled and digitized at 50 Hz on each channel. For each experimental run, raw data were stored on diskettes in separate files.

Data analysis was completed by a universal waveform analyzer (Data Precision DATA6000). Data were smoothed before analysis by a 5 point moving averaging filter. This instrument had the capability of scaling data, filtering, combining channels in various mathematical ways (e.g. computing the anterio–posterior coordinate of the center of force F_z in the *y* direction, y_c), measuring minimum and maximum values, detecting specified level crossing, and differentiation with respect to time. These capabilities were

Table 1. Summary of anthropometric measurements and other data for experimental subjects

Init	S No.	Sex	Age [yr]	Ankle to floor [cm]	Shank length [cm]	Thigh length [cm]	Trunk length [cm]	Center FP to ankle [cm]	Shoe length [cm]	Seat height [cm]	Knee to floor [cm]	Hip to floor [cm]	Sch. to floor [cm]
AK	1	m	51	9.5	37.9	35.2	57.1	5	26.5	42	47.4	104.5	139.7
RJ	2	m	37	11	41	40.5	55.8	5.5	29.6	46	52	107.8	148.3
MM	3	m	26	11.4	42.8	40.8	59.6	3.7	29.4	46	54.2	113.8	154.6
JS	4	m	37	11.6	46.3	38.2	53.2	5.8	29.2	46	57.9	111.1	149.3
TD	5	m	31	11.7	41	43.8	55.7	6.1	30.7	46	52.7	108.4	152.2
TB	6	m	39	12.1	46.8	42	50.7	4.8	30.6	46	58.9	109.6	151.6
IC	7	m	30	11.8	41.8	37.1	55.4	8.6	30.1	46	53.6	109	146.1
ZB	8	m	29	11.5	44.6	41.2	55.8	7.9	28.8	46	56.1	111.9	153.1
MJ	9	m	26	11.7	44.2	41	54.7	10.4	28.1	46	55.9	110.6	151.6
VP	10	m	28	11.6	42.4	37.8	52.6	4.4	28.7	46	54	106.6	144.4
IV	11	m	28	11.7	45.7	43.8	52.6	6.5	29.4	46	57.4	110	153.8
BS	12	m	29	12.8	45	41.2	55.9	7.8	28.9	46	57.8	113.7	154.9
MK	13	m	35	11.7	45.2	41.3	54.7	8.9	30.7	46	56.9	111.6	152.9
DR	14	m	35	13	40.3	39.2	52.9	5.7	30.5	46	53.3	106.2	145.4
AJ	15	f	24	10.8	41.3	37.1	52.7	9.7	30.4	46	52.1	104.8	141.9
AS	16	f	29	10.3	42.2	39.1	53.8	5.1	25.5	46	52.5	106.3	145.4
KV	17	f	37	9.9	41.6	36.1	53.2	4.9	26.2	42	51.5	104.7	140.8
SR	18	f	45	10	38.7	40.5	52.8	5.6	27.3	42	48.7	101.5	142
TK	19	f	29	10.7	38.1	37.1	50.7	9.8	22.5	38	48.8	99.5	136.6
JM	20	f	27	9.7	43	44.3	51.8	10.6	26.4	44	52.7	104.5	148.8
Avg			32.6	11.2	42.5	39.9	54.1	6.8	28.5	44.9	53.7	107.8	147.7
Std dev.			6.7	0.9	2.6	2.6	2.2	2.1	2.1	2.1	3.2	3.8	5.4
Max			51	13	46.8	44.3	59.6	10.6	30.7	46	58.9	113.8	154.9
Min			24	9.5	37.9	35.2	50.7	3.7	22.5	38	47.4	99.5	136.6

FP: force plate.

used to find, according to the latter defined definition, the event values and their time in an automated manner. This device also generated all plots using a digitally controlled plotter (Hewlett-Packard 99872S).

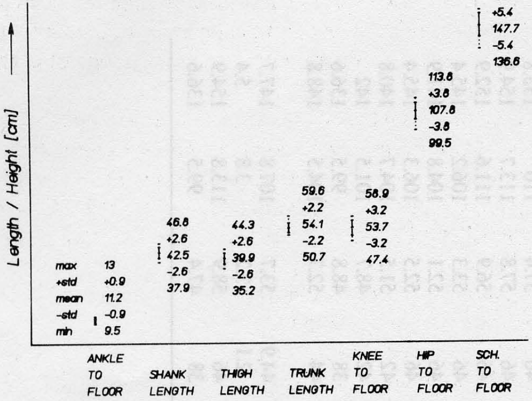

Fig. 1. Graphical presentation of anatomical length data.

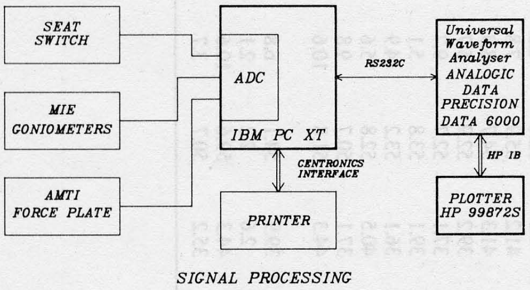

Fig. 2. Measuring system block diagram presentation.

Seat switch. A pair of multi-contact foot switches were placed under the seat to record seat contact. The force sensitivity of this switch was measured to be 5 N, and the contact closure time/bounce interval was 35 ms.

Photographic systems. The black-and-white body markers were placed on body landmarks at the ankle, knee, hip and shoulder as described earlier, and served for photographic calibration verification of goniometric system. The camera was carefully positioned and aligned so that plumb lines placed on each side of the subject were in exact vertical alignment within the field of view.

Experimental protocol

The experimental set-up is shown in Fig. 3. The subject sat on styrofoam blocks, which were used to adjust the seat height. The seat and blocks were placed on the force plate in such a way that the subject's feet were still fully on the plate. A backrest was used to standardize the passive sitting posture with neutral or slight kyphosis. The subject was instructed to touch but not exert significant force on the backrest. If force was applied to the backrest it was free to move out of the standard position and thus was checked after each trial. In this way, the backrest was used only for alignment. Force plate data were recorded together with seat switch closure and goniometric data. In the quiet sitting position, during the rising, quiet standing, sitting down transition, and while sitting quietly, photographs were taken.

After having body markers and goniometers applied, the subject assumed a sitting position on the seat and styrofoam was placed on the force plate. The feet

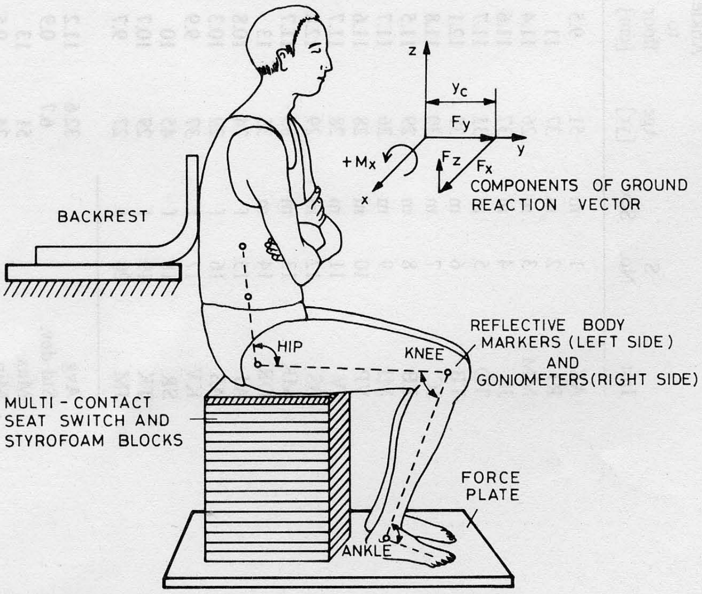

Fig. 3. Schematic display of experimental set-up.

were kept in a uniform separated position by a styrofoam block. Prior to measuring any data, the subject was given the option of raising or lowering the seat height in 2 cm increments to achieve a comfortable seated posture. The anterio–posterior position of the ankle marker with respect to the x-axis of the force plate was carefully measured. The subject was asked to cross the arms in front of the chest. The subject was asked to stand up and sit down in a comfortable and natural manner at a 'normal' speed (whatever speed of movement preferred by the subject). The subject then practiced standing up and sitting down between two and five times to ensure that the goniometers were properly placed and cables properly secured. At least twelve repeated measurements of standing up and sitting down were then collected. The set of at least 12 repeated data measurements was selected for ensuring at least 10 correct data sets. Any trial requiring the recalibration of more than 1 parameter was discarded. Before and after each trial, the goniometers, placement of the feet, and position of backrest were checked, and corrected if necessary. In each trial, computer data collection began with the subject sitting quietly. Two to three seconds after data collection had started, the subject was verbally instructed to stand up. After the subject was fully upright and standing quietly, an additional 2–3 s were allowed to elapse, and the subject was asked to sit down. Once the subject has resumed a quiet seated posture, a final 2–3 s of data were collected. Data collection was then terminated. Typically, between eight and twelve seconds of data were collected for each trial. The primary purpose of this procedure was to ensure that adequate baseline data were present before and after each standing up or sitting down movement, and that the subject was free to move at his/her own selected pace.

RESULTS

Definition

Typical raw experimental data vs time for a single trial from one subject (KV) is given in Fig. 4 and will form the basis for presenting the definitions of event times.

Figure 4 includes hip, knee and ankle angles, the seat switch (4a), orthogonal ground reaction forces $F_y F_z$, and their derivatives (4b), moment M_x, calculated y_c and their derivatives (4c). M_y and M_z were recorded, but not reported here. The horizontal time axis is the same for all traces. Times t_{u0} to t_{u5}, and t_{d0} to t_{d5} are marked on diagrams (see definition of t_{u0} till t_{u5} and t_{d0} till t_{d5} below).

In a similar manner of presentation as Fig. 4, ten trials of standing up from a single subject (TD) are superimposed in Fig. 5. Joint angles and seat switch are shown in (5a), F_y, F_z, M_x and y_c shown in (5b) and derivatives of (5b) quantities in (5c). In Fig. 5, all traces were aligned according to t_{u0}. The diagrams begin 0.5 s before t_{u0}. Average event times which can be read down from the selected diagram are in Fig. 5, marked together with their deviation, both according to ten trials of this subject.

In Fig. 4 the vertical lines (solid, dotted and dashed) represent event times, which separate the phases or periods of the stand up and sit down movement.

From all experimental data collected, six event (marker) times were defined for each standing up movement, and six event times defined for each sitting

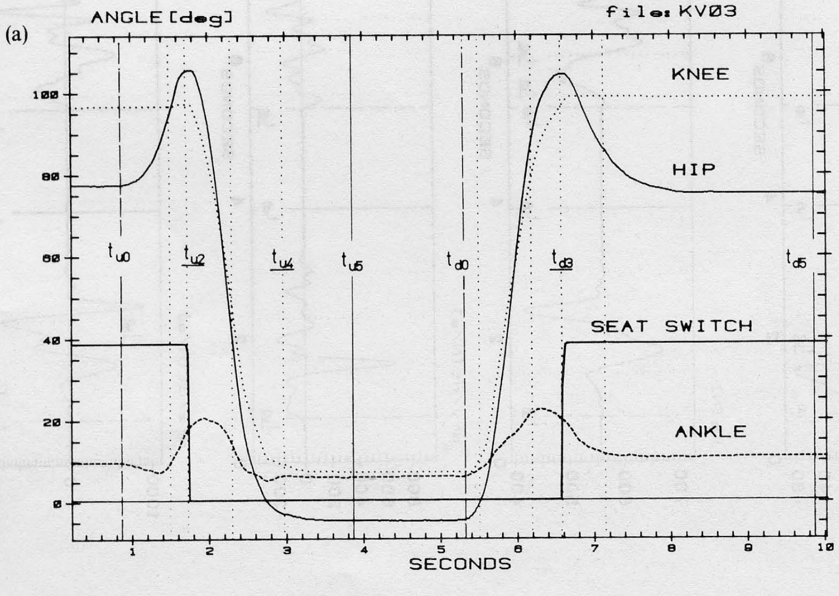

Fig. 4(a).

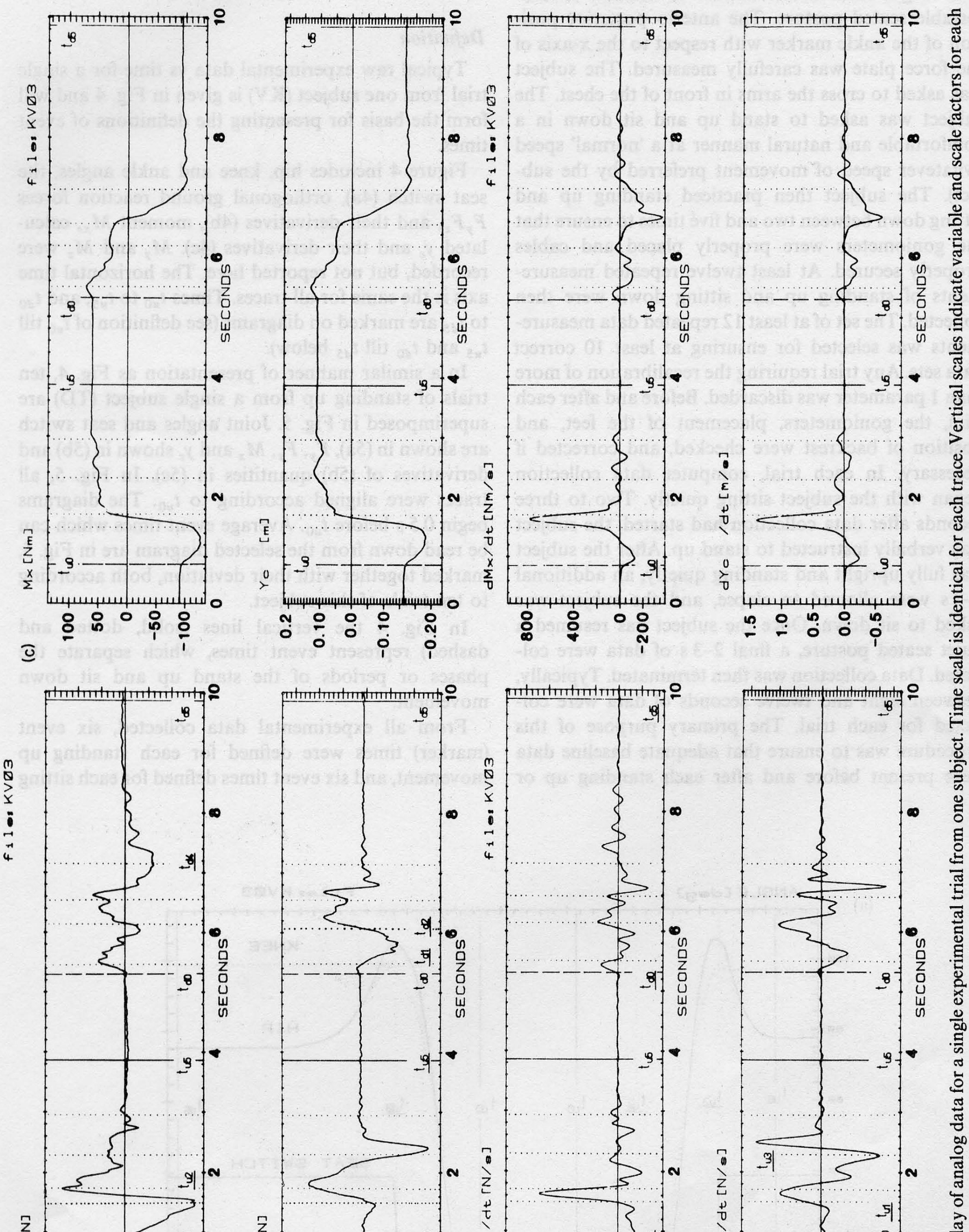

Fig. 4. Display of analog data for a single experimental trial from one subject. Time scale is identical for each trace. Vertical scales indicate variable and scale factors for each trace. Also event markers are included for visualization of event marker characteristics.

down movement. Similar and alike to standing up definitions were made for the sit down movement taking into account a reversal of events.

Figures 6 and 7 schematically illustrate standing up and sitting down events in a diagram. Here the average times of all subject data are expressed in per cent of the total standing up time or sitting down time. These schematic illustrations also present in an or-

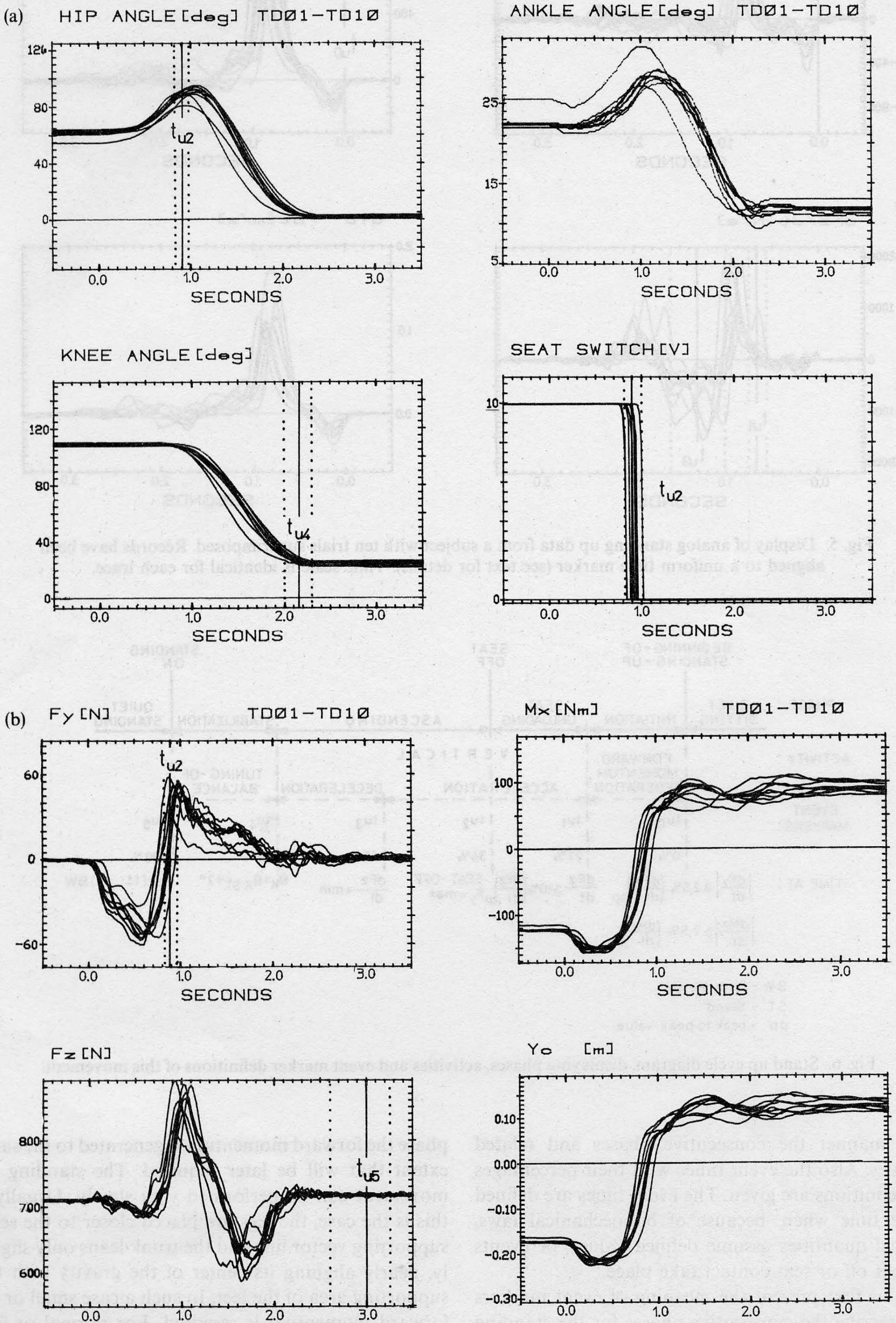

Fig. 5(a), (b).

(c)

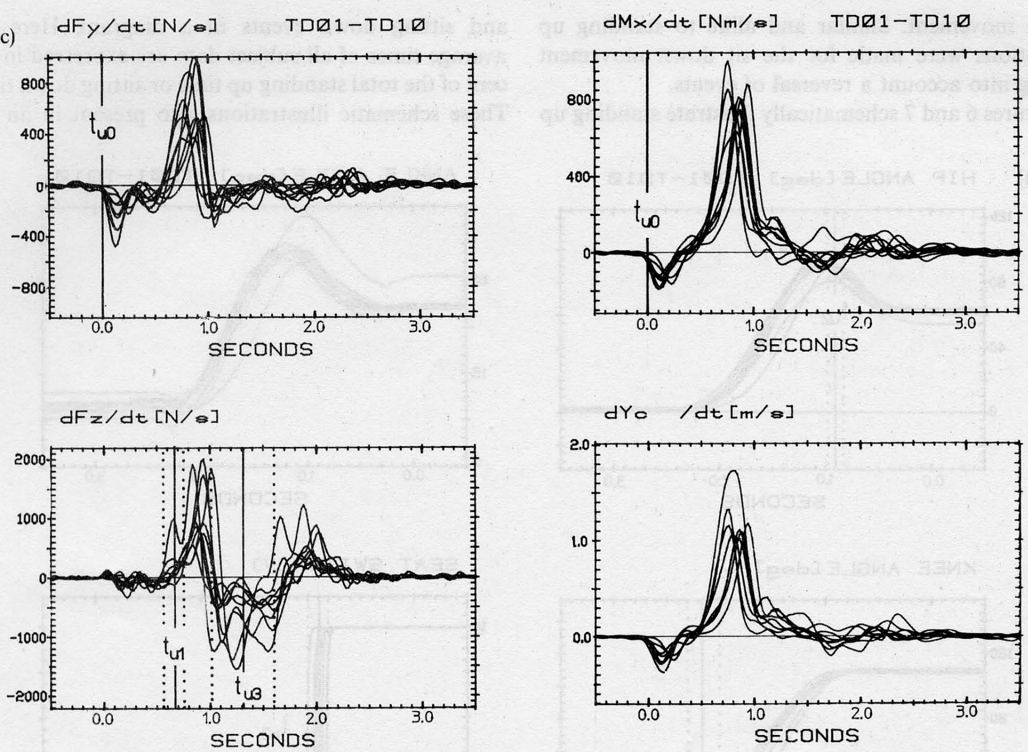

Fig. 5. Display of analog standing up data from a subject with ten trials superimposed. Records have been aligned to a uniform time marker (see text for details). Time scale is identical for each trace.

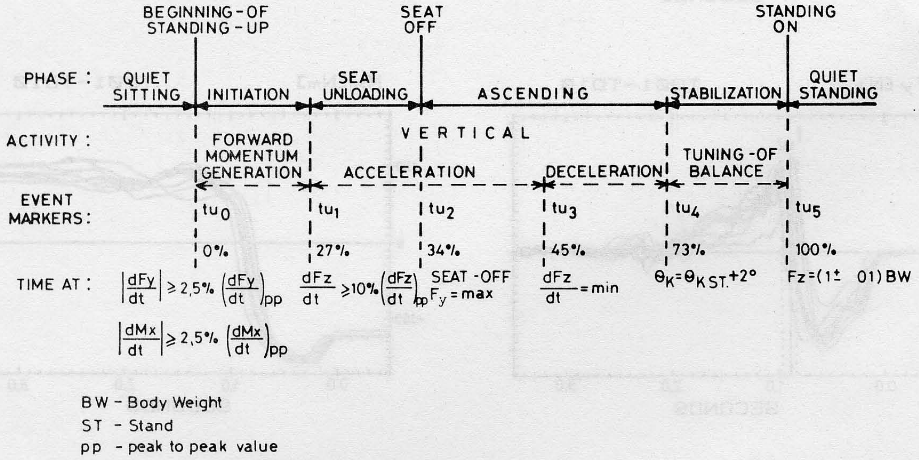

Fig. 6. Stand up cycle diagram, displaying phases, activities and event marker definitions of this movement.

dered manner the consecutive phases and related activities. Also the event times with their percentages and definitions are given. The event times are defined as the time when, because of biomechanical laws, physical quantities assume defined values, or events like seat off or seat contact take place.

Let us first present the meaning of event markers and describe the consecutive phases for the standing up. The quiet sitting is the starting posture for standing up, followed by the initiation phase. During this phase the forward momentum is generated to the same extent that will be later required. The standing up movement can be performed very slowly. Usually if this is the case, the legs are placed closer to the seat-supporting vector line and the trunk leans only slightly, nearly aligning its center of the gravity with the supporting area of the feet. In such a case small or no forward momentum is required. For normal or fast standing up, the movement can be considered to be closer to a ballistic movement, and forward

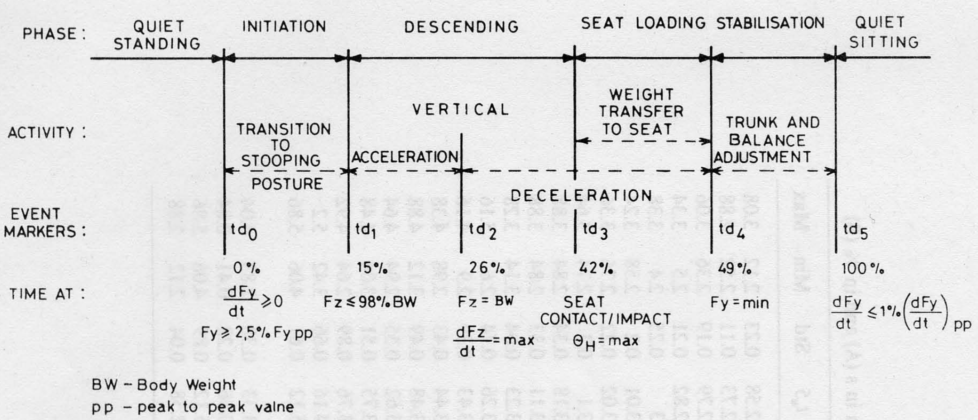

Fig. 7. The cycle diagram presentation for sitting down movement displaying phases, activities and event marker definitions of this movement.

momentum generation is necessary, because of later conversion of the momentum into the F_y force for the supporting vector displacement forward from the seat area to the feet. The starting of the standing up and forward momentum generation is recognized at the time (t_{u0}) when the F_y force is displaying a fast change above the resting fluctuations. Similarly, the starting of standing up can be detected in rapid changing of the M_x torque as is shown in Fig. 5. The starting of the body mass' vertical acceleration is detected by rapid positive changing of vertical F_z force marking the t_{u1} event time and the beginning of seat unloading phase, followed by the seat-off event, defining the t_{u2} time. At this instance the F_y force is at a maximum. After the seat off, the ascending phase starts. During the ascending phase the vertical acceleration is converted to deceleration and when this happens the event is marked for t_{u3}. It can be recognized by the minimum F_z force time derivative. From now on, deceleration of the upward moving body mass is in progress. The vertical upwards movement is ended after the knee is ully extended and at this instance the time t_{u4} is defined, marking the beginning of the stabilization phase, while tuning of the standing balance is in progress. The standing phase starts at the instant when vertical force equals body weight, and the fluctuation of $\pm 1\%$ characteristic for quiet standing are detected. At this instant the time t_{u5} is marked and quiet standing starts.

In Fig. 7 the sitting down phases with related activities, event markers and their definitions are given. The sitting down movement is analogous to standing up, and therefore in a logical reversed order the phases, activities, and event times are defined. Starting from quiet standing, the initiation of sitting down is recognized by the change in the F_y force and superceding the quiet standing fluctuations marking the t_{d0} time and the starting of the activities for changing of the posture from errect standing to stooping posture. Only in such a posture can lowering of the vertical acceleration of the mass be performed. The vertical downward acceleration of body masses is recognized by F_z taking for more than 2 % smaller value compared to body weight (BW). At this instant the event time t_{d1} is selected, and vertical downward acceleration starts, this being the beginning of the descending phase. At the instant when downward acceleration is converted to deceleration, F_z force is equal to BW, and the F_z force displays a maximal shape in changing and the time derivative is maximal ($\mathrm{d}\,F_z/\mathrm{d}t = \max$). This event is marking the t_{d2} time and from now on deceleration is in progress with the descent. The descending phase terminates at the instant of seat contact/impact. This marks the t_{d3} time, and the beginning of the seat loading phase. During this phase, weight is transferred from the legs to the seat. After the F_y force reaches its minimum, the stabilization phase starts and the trunk and balance adjustment activities are in progress. At the instant of $F_y = \min$, the t_{d4} time is defined. The trunk and balance adjustment activities are from now on in progress until such time when F_y force amplitude variations are smaller than 1 %, marking the t_{d5} time, and quiet sitting is in progress. This instant also marks the end of the sitting down movement.

The rationale for choosing the posed event selection and event time definitions and their significance is treated in the discussion. The procedure of determining the event times requires the definition of several threshold values for discriminating events from the steady state fluctuations of each variable seen during normal quiet standing or sitting. The threshold values as displayed and marked in Figs 6 and 7. One per cent, 2.5 % or 10 % of peak-to-peak (pp) have proved to be adequate.

Let us summarize the definitions:

For marking the beginning of standing up, t_{u0} was determined. At that time the initiation phase starts, and is recognized by the first negative change in $\mathrm{d}F_y/\mathrm{d}t$ above 2.5 % of its peak-to-peak value. During the

Table 2. Event times with min, max, average and standard deviation for standing up for all subjects. All times are given in s (A) and in % (B)

(A) Init	t_u1	Std	Min	Max	t_u2	Std	Min	Max	t_u3	Std	Min	Max	t_u4	Std	Min	Max	t_u5	Std	Min	Max
JM	0.7	0.14	0.54	1.06	0.89	0.15	0.74	1.26	1.25	0.16	1.1	1.62	1.78	0.15	1.62	2.08	2.58	0.23	2.12	3.08
DR	0.6	0.08	0.52	0.84	0.83	0.08	0.74	1.06	1.09	0.2	0.86	1.54	1.85	0.15	1.64	2.04	2.73	0.11	2.52	2.88
KM	0.51	0.06	0.44	0.62	0.74	0.07	0.62	0.84	1.17	0.14	0.82	1.3	1.85	0.12	1.62	2.1	2.79	0.19	2.36	3.06
KV	0.67	0.12	0.54	1.02	0.81	0.09	0.8	1.16	1.18	0.18	0.96	1.44	2.05	0.16	1.9	2.44	2.82	0.21	2.5	3.34
TK	0.74	0.09	0.62	0.92	0.97	0.09	0.88	1.14	1.42	0.18	1.08	1.7	2.16	0.13	1.02	2.5	3	0.25	2.4	3.38
TD	0.68	0.07	0.56	0.74	0.89	0.05	0.82	0.94	1.34	0.17	1.08	1.6	2.17	0.09	2	2.3	3.01	0.2	2.58	3.24
AK	0.71	0.09	0.6	0.86	0.89	0.08	0.8	1.02	1.5	0.32	1.2	1.66	2.21	0.18	1.92	2.48	3.02	0.22	2.76	3.36
BS	0.88	0.34	0.54	1.54	1.07	0.34	0.72	1.72	1.33	0.32	0.98	1.94	2.19	0.38	1.82	2.94	3.1	0,3	2.74	3.64
AJ	0.76	0.28	0.4	1.36	1.01	0.25	0.66	1.52	1.5	0.33	1.06	2.06	2.3	0.35	1.9	2.84	3.18	0.34	2.84	3.88
SR	0.76	0.27	0.4	1.36	1.01	0.24	0.66	1.52	1.5	0.32	1.06	2.06	2.3	0.34	1.9	2.84	3.11	0.33	2.84	3.88
RJ	0.64	0.03	0.6	0.68	0.83	0.03	0.8	0.86	1.16	0.23	0.94	1.48	2.24	0.1	2.08	2.42	3.23	0.04	3.14	3.28
IV	0.96	0.73	0.64	2.88	1.17	0.73	0.84	3.1	1.56	0.72	1.24	3.46	2.22	0.74	1.68	4.14	3.26	0.74	2.6	5.16
ZB	0.95	0.3	0.68	1.72	1.12	0.29	0.88	1.88	1.65	0.42	1.14	2.5	2.56	0.44	2.22	3.5	3.43	0.39	2.9	4.16
VP	0.87	0.47	0.48	2.04	1.1	0.46	0.72	2.26	1.44	0.5	0.94	2.52	2.32	0.47	1.9	3.5	3.44	0.43	2.98	4.38
TB	0.74	0.49	0.48	2.2	0.96	0.49	0.72	2.42	1.46	0.5	1.18	2.96	2.58	0.47	2.16	3.92	3.48	0.49	3.12	4.88
JS	0.84	0.3	0.6	1.64	1.13	0.39	0.82	1.86	1.41	0.39	1.08	2.12	2.76	0.45	2.46	3.68	3.62	0.55	2.94	4.64
AS	1.02	0.27	0.68	1.46	1.29	0.28	0.92	1.74	1.44	0.3	1.1	1.94	2.94	0.43	2.24	3.64	3.75	0.51	3.04	4.48
MM	1.54	0.86	0.58	2.46	1.74	0.86	0.8	2.84	2.09	0.84	1.02	3.12	2.99	0.86	2.02	4.14	3.76	0.89	2.64	4.92
MJ	1.5	0.74	0.82	2.94	1.73	0.75	1.02	3.12	2.05	0.87	1.22	3.64	3.1	0.74	2.36	4.42	4.16	0.66	3.42	5.2
CI	2.11	0.7	1.08	2.88	2.41	0.63	1.3	3.08	2.87	0.84	1.5	4.28	4.21	0.64	3.06	4.92	5.12	0.61	4.06	5.86
Avg	0.91	0.32	0.59	1.56	1.13	0.32	0.81	1.77	1.52	0.40	1.08	2.25	2.44	0.37	1.98	3.14	3.33	0.38	2.83	4.04
Std	0.38	0.25	0.15	0.75	0.39	0.25	0.15	0.77	0.40	0.24	0.15	0.82	0.55	0.23	0.40	0.85	0.56	0.22	0.41	0.84
Max	2.11	0.86	1.08	2.94	2.41	0.86	1.30	3.12	2.87	0.87	1.50	4.28	4.21	0.86	3.06	4.92	5.12	0.89	4.06	5.86
Min	0.51	0.03	0.40	0.62	0.74	0.03	0.62	0.84	1.09	0.14	0.82	1.30	1.78	0.09	1.02	2.04	2.58	0.04	2.12	2.88

All times are in s.

Table 2(B)

Init	t_u1	Std	t_u2	Std	t_u3	Std	t_u4	Std	t_u5	Std
JM	27.1	5.4	34.5	5.8	48.4	6.2	69.0	5.8	100.0	8.9
DR	22.0	2.9	30.4	2.9	39.9	7.3	67.8	5.5	100.0	4.0
KM	18.3	2.2	26.5	2.5	41.9	5.0	66.3	4.3	100.0	6.8
KV	23.8	4.3	28.7	3.2	41.8	6.4	72.7	5.7	100.0	7.4
TK	24.7	3.0	32.3	3.0	47.3	6.0	72.0	4.3	100.0	8.3
TD	22.6	2.3	29.6	1.7	44.5	5.6	72.1	3.0	100.0	6.6
AK	23.5	3.0	29.5	2.6	49.7	10.6	73.2	6.0	100.0	7.3
BS	28.4	11.0	34.5	11.0	42.9	10.3	70.6	12.3	100.0	9.7
AJ	23.9	8.8	31.8	7.9	47.2	10.4	72.3	11.0	100.0	10.7
SR	24.4	8.7	32.5	7.7	48.2	10.3	74.0	10.9	100.0	10.6
RJ	19.8	0.9	25.7	0.9	35.9	7.1	69.3	3.1	100.0	1.2
IV	29.4	22.4	35.9	22.4	47.9	22.1	68.1	22.7	100.0	22.7
ZB	27.7	8.7	32.7	8.5	48.1	12.2	74.6	12.8	100.0	11.4
VP	25.3	13.7	32.0	13.4	41.9	14.5	67.4	13.7	100.0	12.5
TB	21.3	14.1	27.6	14.1	42.0	14.4	74.1	13.5	100.0	14.1
JS	23.2	8.3	31.2	10.8	39.0	10.8	76.2	12.4	100.0	15.2
AS	27.2	7.2	34.4	7.5	38.4	8.0	78.4	11.5	100.0	13.6
MM	41.0	22.9	46.3	22.9	55.6	22.3	79.5	22.9	100.0	23.7
MJ	36.1	17.8	41.6	18.0	49.3	20.9	74.5	17.8	100.0	15.9
CI	41.2	13.7	47.1	12.3	56.1	16.4	82.2	12.5	100.0	11.9
Avg	26.5	9.1	33.2	8.9	45.3	11.3	72.7	10.6	100.0	11.1
Std	6.1	6.4	5.7	6.5	5.3	5.4	4.1	5.8	0.0	5.4
Max	41.2	22.9	47.1	22.9	56.1	22.3	82.2	22.9	100.0	23.7
Min	18.3	0.9	25.7	0.9	35.9	5.0	66.3	3.0	100.0	1.2

All times are expressed relative to t_u5.

standing up initialization phase forward momentum is generated until the vertical acceleration starts by time t_{u1}.

Time t_{u1} was determined when dF_z/dt first exceeded in positive direction the threshold of 10 % of its resting peak-to-peak value.

Time t_{u2} was determined by the opening of the seat switch and indicated the event termed 'seat off'.

Time t_{u3} was determined at the point of the $dF_z/dt = \min$, indicating the end of the vertical acceleration period.

Time t_{u4} marks the end of vertical deceleration and ascending phase. It was determined as the marker time When Θ_k fell below a threshold. This threshold represents two degrees away from Θ_k as displayed in the standing posture (Fig. 4).

Time t_{u5} was determined as the time at which F_z settled to within 1 % of its resting and steady state value being a measure of quiet standing. For sitting down, six event times were also defined and measured.

Time t_{d0} marks the beginning of sit movement and was defined as the time when change in F_y in a positive direction exceeds 2.5 % of its peak-to-peak value. At this time transition from quiet standing to stooping posture takes place and is followed by the descending phase when F_z starts to decrease. At that instance time t_{d1} was defined. Time t_{d1} is the time at which F_z falls below 98 % of BW.

At time t_{d2}, the downward movement acceleration ends. F_z is crossing the zero value in a positive direction, and at that instance $dF_z/dt = \max$.

Time t_{d3} was determined by the closure of the seat switch defining the beginning of seat loading phase and the weight transfer to seat is started.

Time t_{d4} was defined as the time when $F_y = \min$, indicating that the trunk balance adjustments will start and that the weight transfer to the seat was completed because from now on F_z starts to settle to BW.

Finally, time t_{d5} was defined as the time when F_y has settled to within 1 % of its steady state value during quiet sitting.

Normative data

The averages and standard deviations (for between 10 and 12 trials) of all time measurements for each subject are given in Table 2A for standing up and in Table 3A for sitting down. Tables 2B and 3B present the average data normalized to the duration of the movement (t_{u5} and t_{d5} respectively) and expressed in per cent. For visual assessment in Fig. 8 the data of Tables 2A and 2B are graphically displayed. At a glance it is evident that sitting down on average takes longer, and time variations are enlarged compared with the standing up movement. Based on data for all subjects, the average time (standard deviation) to stand up was 3.33 s (0.56) and the average time to sit down was 4.62 s (0.41). These two means were significantly different ($t = 20.7$, df $= 407$, $p < 0.005$), this is a result of the fact that sitting down is performed slower and with more precaution. For individual subjects, the fastest and slowest average times to stand up were 2.58 s (0.23) and 5.12 s (0.61), respectively. For individual subjects sitting down, the fastest and slowest

Table 3. Event times with min, max, average and standard deviation for sitting down for all subjects. All times are given in s (A) and in % (B)

(A) Init	*td*1	Std	Min	Max	*td*2	Std	Min	Max	*td*3	Std	Min	Max	*td*4	Std	Min	Max	*td*5	Std	Min	Max
JM	0.47	0.15	0.24	0.68	0.9	0.27	0.46	1.22	1.39	0.15	1.08	1.56	1.52	0.18	1.16	1.8	4.02	0.41	3.22	4.48
DR	0.54	0.26	0.3	1.08	1.01	0.25	0.76	1.56	1.48	0.25	1.24	2.06	1.95	0.27	1.64	2.54	4.26	0.49	3.56	5.2
KM	0.4	0.22	0.18	0.88	0.96	0.32	0.42	1.46	1.57	0.25	1.3	2.1	1.85	0.33	1.46	2.66	4.27	0.4	3.4	4.92
KV	0.35	0.16	0.16	0.78	0.81	0.15	0.62	1.2	1.29	0.23	1.1	1.96	1.63	0.3	1.3	2.18	4.01	0.41	2.96	4.58
TK	0.93	0.41	0.18	1.48	1.53	0.44	0.96	2.22	2.12	0.41	1.48	2.76	2.48	0.5	1.62	3.02	4.97	0.54	3.8	5.66
TD	0.9	0.68	0.2	2.14	1.52	0.7	0.74	2.84	2.23	0.7	1.42	3.56	2.7	0.73	1.8	4.16	4.86	0.79	3.72	6.18
AK	0.65	0.49	0.1	1.4	1.15	0.48	0.58	1.9	1.91	0.49	1.26	2.5	2.33	0.48	1.74	3	4.15	0.6	3.24	4.94
BS	0.81	0.27	0.46	1.48	1.42	0.29	1.02	2.12	1.85	0.32	1.48	2.64	2.26	0.35	1.94	3.12	4.57	0.5	3.48	5.72
AJ	0.99	0.39	0.46	1.66	1.44	0.4	1.08	2.3	2.25	0.51	1.54	2.9	2.55	0.44	1.72	3.08	4.79	1.23	2.52	66.12
SR	1	0.4	0.46	1.66	1.45	0.41	1.08	2.3	2.26	0.52	1.54	2.9	2.56	0.45	1.72	3.08	4.79	1.23	2.52	6.12
RJ	1.1	1.09	0.2	3.18	1.61	1.12	0.72	3.72	2.38	1.11	1.42	4.5	2.76	0.98	1.98	4.68	5.38	1.43	3.24	7.68
IV	0.66	0.28	0.26	1.1	1.18	0.27	0.76	1.6	1.77	0.25	1.3	2.1	2.03	0.35	1.42	2.38	4.34	0.4	3.88	5.12
ZB	0.13	0.06	0.02	0.2	0.6	0.3	0.1	0.92	1.57	0.18	1.22	1.9	1.78	0.23	1.36	2.1	4.27	0.57	2.92	4.92
VP	0.88	0.28	0.52	1.42	1.25	0.35	0.82	1.86	2.03	0.23	1.64	2.46	2.48	0.29	1.98	2.88	4.78	0.29	4.46	5.28
TB	0.36	0.16	0.12	0.64	1.04	0.18	0.74	1.28	1.81	0.24	1.3	2.14	2.1	0.25	1.6	2.5	4.23	0.56	3.28	5.02
JS	0.95	0.52	0.2	1.66	1.36	0.7	0.28	2.14	2.21	0.52	0.96	2.94	2.47	0.54	1.16	3.12	4.71	0.72	2.86	5.44
AS	1.17	0.3	0.74	1.52	1.71	0.36	1.26	2.18	2.37	0.28	2.04	2.68	2.67	0.32	2.28	3.1	5.28	0.58	4.42	6.08
MM	1.08	0.67	0.28	2.28	1.68	0.7	0.8	2.96	2.16	0.68	1.24	3.42	2.65	0.58	1.82	3.56	5.17	0.76	4.14	6.64
MJ	0.3	0.14	0.14	0.6	0.76	0.27	0.34	1.04	1.68	0.23	1.42	2.04	2.18	0.29	1.88	2.7	4.52	0.57	3.54	5.26
CI	0.72	0.17	0.42	1.02	1	0.21	0.68	1.4	2.32	0.16	2.1	2.64	2.76	0.3	2.34	3.46	5.06	0.37	4.36	5.68
Avg	0.72	0.36	0.28	1.34	1.22	0.41	0.71	1.91	1.93	0.39	1.40	2.59	2.29	0.41	1.70	2.96	4.62	0.64	3.48	8.55
Std	0.30	0.24	0.17	0.66	0.32	0.23	0.29	0.69	0.34	0.23	0.28	0.67	0.38	0.19	0.32	0.66	0.41	0.30	0.57	13.25
Max	1.17	1.09	0.74	3.18	1.71	1.12	1.26	3.72	2.38	1.11	2.10	4.50	2.76	0.98	2.34	4.68	5.38	1.43	4.46	66.12
Min	0.13	0.06	0.02	0.20	0.60	0.15	0.10	0.92	1.29	0.15	0.96	1.56	1.52	0.18	1.16	1.80	4.01	0.29	2.52	4.48

All times are in s.

Table 3(B)

Init	*td*1	Std	*td*2	Std	*td*3	Std	*td*4	Std	*td*5	Std
JM	11.7	3.7	22.4	6.7	34.6	3.7	37.8	4.5	100.0	10.2
DR	12.7	6.1	23.7	5.9	34.7	5.9	45.8	6.3	100.0	11.5
KM	9.4	5.2	22.5	7.5	36.8	5.9	43.3	7.7	100.0	9.4
KV	8.7	4.0	20.2	3.7	32.2	5.7	40.6	7.5	100.0	10.2
TK	18.7	8.2	30.8	8.9	42.7	8.2	49.9	10.1	100.0	10.9
TD	18.5	14.0	31.3	14.4	45.9	14.4	55.6	15.0	100.0	16.3
AK	15.7	11.8	27.7	11.6	46.0	11.8	56.1	11.6	100.0	14.5
BS	17.7	5.9	31.1	6.3	40.5	7.0	49.5	7.7	100.0	10.9
AJ	20.7	8.1	30.1	8.4	47.0	10.6	53.2	9.2	100.0	25.7
SR	20.9	8.4	30.3	8.6	47.2	10.9	53.4	9.4	100.0	25.7
RJ	20.4	20.3	29.9	20.8	44.2	20.6	51.3	18.2	100.0	26.6
IV	15.2	6.5	27.2	6.2	40.8	5.8	46.8	8.1	100.0	9.2
ZB	3.0	1.4	14.1	7.0	36.8	4.2	41.7	5.4	100.0	13.3
VP	18.4	5.9	26.2	7.3	42.5	4.8	51.9	6.1	100.0	6.1
TB	8.5	3.8	24.6	4.3	42.8	5.7	49.6	5.9	100.0	13.2
JS	20.2	11.0	28.9	14.9	46.9	11.0	52.4	11.5	100.0	15.3
AS	22.2	5.7	32.4	6.8	44.9	5.3	50.6	6.1	100.0	11.0
MM	20.9	13.0	32.5	13.5	41.8	13.2	51.3	11.2	100.0	14.7
MJ	6.6	3.1	16.8	6.0	37.2	5.1	48.2	6.4	100.0	12.6
CI	14.2	3.4	19.8	4.2	45.8	3.2	54.5	5.9	100.0	7.3
Avg	15.2	7.5	26.1	8.6	41.6	8.1	49.2	8.7	100.0	13.7
Std	5.5	4.5	5.3	4.2	4.6	4.3	5.0	3.4	0.0	5.7
Max	22.2	20.3	32.5	20.8	47.2	20.6	56.1	18.2	100.0	26.6
Min	3.0	1.4	14.1	3.7	32.2	3.2	37.8	4.5	100.0	6.1

average times were 4.01 s (0.41) and 5.38 s (1.43). There was a statistically significant difference for both standing up and sitting down fastest and slowest subjects (standing: $t = 13.38$, df $= 22$, $p < 0.005$; sitting $t = 3.18$, df $= 21$, $p < 0.005$).

DISCUSSION

Proper interpretation of pathology typically requires quantification, and comparison with established normal limits. In studying the biomechanics of gait, the gait cycle diagram is used to quantify walking performance. The value of this diagram is in its logic description with definition of events of the gait cycle and in the possibility to express the quantities in percentage terms, which enables data comparison, since individuals walk at varying speeds. The present study has attempted to provide a similar conceptualization for the movements of standing up and sitting down.

The earliest indication that the subject is initiating the act of standing up is a change in F_y (as reflected by $\mathrm{d}F_y/\mathrm{d}t$). This force change indicates that forward momentum is generated. This is necessary for the latter in time, forward transfer of supporting vector from the seat to the feet while standing will be initiated. In hands-supported standing up this is not the case. The time at which this change occurred and exceeded the resting value of the 2.5 % $\mathrm{d}F_y/\mathrm{d}t$ peak-to-peak was defined as t_{u0}, which served as the zero reference time for subsequent definition of standing up event times. This value of 2.5 % $\mathrm{d}F_y/\mathrm{d}t$ peak-to-peak was selected after observing the average steady state fluctuation in a number of subjects. This time marks as described, the beginning of the initiation phase, in which the forward momentum starts to be generated. It is interesting to note that during this phase, y_c first moves in the negative (backward) direction for several cm. This is due to the need to generate forward momentum. Note that while seated the subject has no means to execute a horizontal F_y force and this force can be only dynamically generated by the trunk mass' (m) forward leaning velocity. Once required velocity is reached, fast breaking sets in by the trunk and hip extension muscles, providing the compensation of the downward component and partly adding to the y direction component of linear momentum mv. The downward rotating trunk masses (m) are due to gravity and hip with trunk flexors accelerated for instance to mv_1. At reaching some forward leaning α angle, the trunk and hip extensors rapidly produce an extension impulse of force which corresponds in value with the momentum of mv_1, but with the opposite and predominantly upwards direction. The composition of these two quantities results in a momentum acting predominantly in the y direction having the value of $mv_y = \int_0^t F_y(t)\,\mathrm{d}t$, meaning that because of the law of conservation of momentum, a given F_y force can act t-time on the body mass m to accelerate it in the y direction and hence move the body forward. The trunk forward leaning impulse of force and breaking is measured by the force plate and recorded as displayed in the figures. A similar force or impulse of force can be generated by means of hands in case hands-assisted standing up is performed, and parallel bars or similar devices are used. Once sufficient momentum has been gained, the

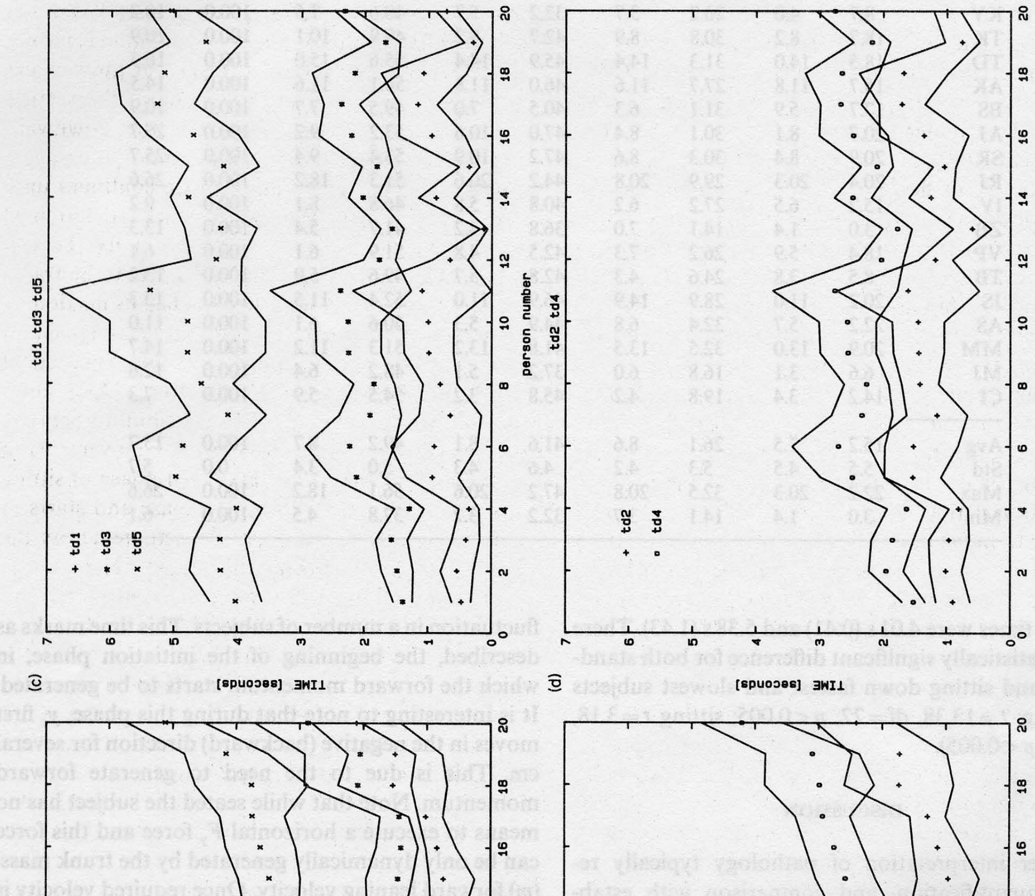

Fig. 8. Graphical presentation of standing up and sitting event times with standard deviations for all measured subjects.

phase of vertical acceleration begins at time t_{u1} with a positive increase of vertical force as observed in dF_z/dt followed by a rapidly rising course. While the forward momentum is generated also dF_z/dt shows fluctuations, which are usually in a 5 % limit and therefore for ensuring a safe margin the value of 10 % of peak-to-peak value for dF_z/dt was selected. After time t_{u1} the acceleration and the seat unloading phase starts. In this segment that portion of the body weight (BW) born by the seat during sitting is fully transferred to the legs. The seat unloading period ends with the event termed 'seat off' (the switch opens) at time t_{u2} when F_y =max, hip is in flexion, and the ascending period begins. In the ascending period of the vertical acceleration phase, the body segments above the hip begin to move with the entire BW now born by the legs. In this period, the hip and knee joints move rapidly into extension. The vertical acceleration phase ends with F_z crossing the resting value in the negative direction, being appropriately discriminated by the minimum of dF_z/dt. At that instant, time t_{u3} is defined, and the vertical deceleration phase begins. The vertical ascending phase is composed of two periods: an acceleration period in which the knee and hip joints continue to move into extension (over the interval t_{u2} to t_{u3}), and a deceleration period in which the forces (F_z and F_y) return to BW and zero, respectively. When the knee joint angle comes to within 2° of the average joint angle during stance, the ascending period and the vertical deceleration phase ends (t_{u4}). The stabilization period begins at time t_{u4}. At the time that standing up has been essentially completed, the body begins to assume a characteristic standing posture, (Bajd *et al.*, 1982; Quintern, 1987) while balance tuning is still in progress. Quiet standing may be considered as a reference or an average posture about which minute fluctuations occur. In this posture about which minute fluctuations occur. In this posture F_z does not vary more than 1 % of BW. The longest settling time of these two forces (F_z and F_y) determines the end of the stabilization period hence the time t_{u5}. This is the end of standing up and the beginning of quiet stance.

The earliest indication that the subject is initiating the act of sitting down is a change in F_y in the positive direction, being a consequence of the impulse generation for moving the body weight backward in a y direction toward the seat. This is defined as t_{d0}. The threshold in this case was determined as 2.5 % F_y peak-to-peak, because during the quiet standing, F_y typically fluctuates within the 2.5 % of F_y peak-to-peak. Time t_{d0} served as the zero reference time for all subsequent times, and marks the beginning of the initiation phase of sitting down. This change in F_y is produced by a movement of the body into the so-called 'stooping position', a posture which is essentially never observed during quiet stance. This destabilizes the body from the forces and positions seen during quiet stance. The body segments then begin to move rapidly into flexion, and F_z becomes less than BW at time t_{d1}. Time t_{d1} is measured as the instant when F_z declines to 98 % of BW. This 2 % threshold was determined according to F_z fluctuations which are small during quiet stance, but increase rapidly during the act of sitting down. At this time the initiation phase ends and the vertical (downward) acceleration phase begins. F_z continues to decrease, reaches a minimum, and then rises back to BW value. The time when dF_z/dt displays its maximum is termed t_{d2}. This marks the end of the vertical (downward) acceleration phase and the beginning of the vertical deceleration phase. In this phase, the downward movement enters the braking phase and F_z once again exceeds BW. This deceleration phase continues until time t_{d3}, closure of the seat switch, which is determined by the impact of the seat. At this instance the seat loading phase begins and the BW starts to be transferred to the seat. Hip angle has reached its maximum. This phase of weight transfer to seat is completed at t_{d4}, when F_y assumes its minimum value. Subsequent to this time F_z has smaller fluctuation. Upon completion of seat loading, the BW distribution between the legs and seat is influenced only by movements of the body above the trunk. This final phase of sitting down is termed the stabilization phase and starts at t_{d4}. Both F_z and F_y continue to fluctuate across the steady state value during this phase. The longest settling time of these two forces is termed t_{d5} and defined for F_y settling to within 1 %. The fluctuation of F_z ends before time t_{d5}. This marks the end of the stabilization phase and the end of sitting down and the subject is now defined to be at rest. At this rest position small fluctuations of F_y continue, which are due to the trunk and partly to the hip movement.

The data collected in this study indicate that standing up is accomplished more rapidly than sitting down (difference in means approximately 1.3 s). The variances for data from all subjects for standing up and sitting down are quite comparable. The reason for the difference in average time required for standing up 3.33 s to 4.62 s for sitting down can be recognized by considering the net time required for deceleration and stabilization for standing up (t_{u5}–t_{u3}), 1.81 s against the net time for deceleration and trunk balance adjustment for sitting down, (t_{u5}–t_{u2}) of 3.40 s. The difference is 1.59 s and the reason for it is that in sitting down, deceleration works against gravity, and while doing so the movement is executed with more precaution. Also subjects might employ a slower movement in sitting down because of lack of visual information and uncertainty regarding the location of the endpoint (seat).

In Fig. 6 the phases and events are graphically presented in diagrammatic form for standing up and in Fig. 7 for sitting down. There is an analogy between stand up and sit down phases and events. This is logical and recognizable by comparing both diagrams. The standing up phase diagram observed in the reverse direction is similar to the sitting down diagram. Appropriate substitution of phase names (ascending for descending) and seat (loading for unloading), results in the phase diagram for sitting down.

For the standing up initiation, forward momentum must be generated, while for sitting down initiation, the destabilization takes place by transition to the stooping posture, and downward acceleration for vertical descending can be started, while in standing up after the initiation phase, vertical acceleration and seat unloading takes place and continues into the ascending phase. In such a logical manner all phases can be compared. Also note that during each phase a determined activity takes place and appropriate activation of effectors is necessary, and in this regard also an analogy to the gait cycle diagram can be established, with similar expected usefulness. The latter is particularly important in clinical work for diagnosis of patients and concise but still precise description of their standing up or sitting down characteristics. For clinical utilization standing up and sitting down data can be relatively easily and repetitively collected if a motion system is used like ELITE® (ELITE—BTS Bioengineering Technology and Systems) or Watsmart® (WATSMART—WATerloo Spatial Motion Analysis and Recording Technique) with a force plate, because only reflective markers have to be placed on centers of joints and all the rest performed by the measuring system. Simplified but still sufficient set off data for clinical use are at present not defined, but it is expected that future work may define clinical useful simplified procedures. Comparing standing up with sitting down inter- and intra-individual differences with similar values in gait would be of interest and might be of important diagnostic value. The question of how standing up and sitting down deviations influence gait and gait differences is at present not known, but could later prove to be meaningful. Detailed correlation studies of quantities related to event time definitions are in preparation and may additionally prove or even disprove some of our definitions and expectations.

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