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Sequencing sit-to-stand and upright posture for mobility limitation assessment: determination of the timing of the task phases from force platform data

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Abstract

The identification of quantitative tools to assess an individual's mobility limitation is a complex and challenging task. Several motor tasks have been designated as potential indicators of mobility limitation. In this study, a multiple motor task obtained by sequencing sit-to-stand and upright posture was used. Algorithms based on data obtained exclusively from a single force platform were developed to detect the timing of the motor task phases (sit-to-stand, preparation to the upright posture and upright posture). To test these algorithms, an experimental protocol inducing predictable changes in the acquired signals was designed. Twenty-two young, able-bodied subjects performed the task in four different conditions: self-selected natural and high speed with feet kept together, and self-selected natural and high speed with feet pelvis-width apart.

The proposed algorithms effectively detected the timing of the task phases, the duration of which was sensitive to the four different experimental conditions. As expected, the duration of the sit-to-stand was sensitive to the speed of the task and not to the foot position, while the duration of the preparation to the upright posture was sensitive to foot position but not to speed.

In addition to providing a simple and effective description of the execution of the motor task, the correct timing of the studied multiple task could facilitate the accurate determination of variables descriptive of the single isolated phases, allowing for a more thorough description of the motor task and therefore could contribute to the development of effective quantitative functional evaluation tests.

Keywords: Sit-to-stand; Upright posture; Motor ability assessment; Ground reaction forces

1. Introduction

The quantitative assessment of an individual's function along a continuum of disease, disability, and functional independence is of paramount importance for evaluating the effectiveness of rehabilitation interventions [1,2]. In rehabilitation medicine, the assessment of skills is often considered to be more important than a detailed analysis of forces, joint angles and muscle activation [3]. Mobility limitations are typically present as early manifestations of a disablement process and can predict disability progression [4,5]. Various tests have been proposed to assess these limitations, which include the observation of an individual performing selected motor tasks, and which provide semi-quantitative measures based on predefined scales [6,7]. Quantitative methods have been also proposed. An index obtained from a combination of physical performance tests, body measurements, spirometry and other semi-quantitative measurements was proposed to assess mobility limitations [8]. Similarly, to quantify the individual's gait deviation from the average normal gait, an index named ''normalcy index'' based on principal component analysis of gait variables such as cadence and joint angle ranges, was proposed

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[9]. Despite these efforts, the definition of effective quantitative tools to assess mobility remains a complex and challenging process.

The motor tasks to analyse should be selected based on the amount of muscle strength and range of motion required to perform it, and should also challenge balance. Several motor tasks, such as stair negotiation (SN) [10], sit-to-stand (STS) [11–13], level walking [9,14], and upright posture (UP) [15,16] have been investigated with the purpose of providing quantitative information regarding the individual's functional status. These are often included in physical performance tests used in clinical practice [6,7,17–19]. STS and SN have been identified as the most mechanically demanding motor tasks among activities of daily living [10,20], confirming the general acceptance of their effectiveness as indicators of mobility level.

In order to obtain reliable data from individuals performing such motor tasks in the unnatural surrounding of a laboratory, two major aspects should be carefully addressed:

1) the instrumentation should be minimally perceived by the individual;
2) the motor task should be chosen among those typically performed during the daily activity, so that the motor strategies used by the individuals are not affected by motivation and learning.

To respond to the above-mentioned points, a method based on the use of a single measurement instrument (a force platform) and a simple mechanical model incorporating the a priori available knowledge of both the task and the individual's anthropometry was applied to the STS motor task [2,21,22]. A similar approach was recently used to obtain an outcome measure for individuals with stroke [23]. The vertical ground reaction force was monitored to provide a continuous measure of weight-bearing ability and postural stability with the least inconvenience for the tested individuals. Standard instructions for foot positioning and thigh placement, in order to improve the reliability of the STS evaluation, were recommended.

Combining different motor tasks is often believed to provide additional information regarding the individual's mobility. Combined motor and cognitive tasks have been shown to be effective in assessing the level of mobility and in predicting falls of individuals with cognitive impairments [24–31], but less effective for individuals whose falls are caused largely by mobility limitations, such as individuals affected by Parkinson's disease. To respond to this limitation a multiple motor task obtained by sequencing STS and gait initiation has been proposed [32]. An essential requirement to make such tests effective is the ability to determine the duration of the distinct motor tasks forming the multiple task and of the transitions between them.

Based on the hypothesis that a multiple motor task can potentially reveal more information than a single motor task, we investigated the motor task obtained by sequencing STS and UP (STS-to-UP). In particular, we hypothesized that the STS-to-UP task is composed of three phases: the STS, a transition in preparation to UP (pUP) and the UP. In accordance to the previously mentioned minimal instrumentation criteria, algorithms for the detection of the phases of the STS-to-UP based solely on force platform data are here presented.

2. Materials and methods

2.1. Subjects and protocol

Twenty-two able-bodied volunteers participated in the study (13 females and 9 males, age 22 ± 3 years). Informed consent was provided. Prior to task data acquisition, the following anthropometric measurements were manually performed: body mass (62.0 ± 9.2 kg), stature (1.69 ± 0.09 m), foot length (0.24 ± 0.02 m) and pelvis width (0.23 ± 0.13 m). Subjects were asked to sit on a height-adjustable seat [33], the level of which was set at the knee height and located on a force platform (six-component, strain-gage Bertec, 400 mm × 800 mm), facing a target positioned 3 m away from the subject and at the same height as the eyes of the subject (measured while standing). Light and sound conditions were kept under control during the entire data acquisition session. Subjects were asked to position their feet parallel on the force platform and forming a 90° angle with the shank and to keep their trunk vertical and their arms folded across their chest [20]. Feet positions were traced on the plate to ensure exact repositioning after each trial. Subjects were instructed on how to perform the STS-to-UP task by watching a computer visual simulation of it and could practice the task before data acquisition to reduce possible learning effects.

Since the validity of the results of the algorithms proposed for the detection of the three phases that compose the motor task could not be assessed by means of uncorrelated measurements nor could a simulation of the motor task be implemented, the following experimental protocol was designed to induce predictable changes in the recorded signals. Subjects were asked to perform the STS-to-UP task five times in each of the following four different conditions: (1) self-selected natural speed with feet kept together (NFT); (2) self-selected high speed with feet together (HFT); (3) self-selected natural speed with feet pelvis-width apart (NFA); and (4) self-selected high speed with feet pelvis-width apart (HFA). The four different experimental conditions listed above were chosen so that both "dynamic" (STS) and "static" (UP) phases could be challenged [21]. STS duration was hypothesised to be invariant to medio-lateral changes of the base of support, while the pUP duration was hypothesised to be invariant to task execution speed.

The ground reaction forces (GRF) were measured and the centre of pressure (CoP) displacement was computed. Each acquisition lasted 30 s to ensure reliability and validity of stability measures [34]. The accuracy of the force platform in locating the CoP position was estimated to be within 1 mm. Force platform data were sampled at 100 frames per second by a 16-bit A/D converter acquisition board (National Instruments Inc., Austin, TX). Data were filtered using a digital, low-pass, second-order, Butterworth filter. Cut-off frequency was set at 15 Hz.

2.2. Data analysis

Three different algorithms were developed to detect the following time instants from force platform signals:

1) the beginning of the STS (t_{STS});
2) the beginning of the pUP phase (t_{pUP}), which is coincident with the end of the STS phase;
3) the beginning of the steady UP (t_{UP}), which is coincident with the end of the pUP phase.

We are aware that describing gradual transitions from one phase to the following, such as the transition from pUP to UP, with instantaneous time-event markers is an important simplification that could affect the reliability of such time markers. However, we also believe that the information gained by dividing the task in phases can disclose insights regarding the individual's functional performance. When similar motor tasks were studied [35,36], the different phases of the analysed multiple motor tasks were not distinguished, hence limiting the effectiveness of the extracted variables.

Whereas the first two events were determined directly from the GRF signals, the third one was determined from the CoP trajectory.

The beginning of the STS causes a rapid change of the body centre of mass displacement in the anterior–posterior direction [37], which reflects on the corresponding GRF component. The time instant t_{STS} was thus chosen as the sample corresponding to the zero crossing of the straight line joining the points over the first region of positive slope at 20% and 80% of the peak value of the anterior–posterior GRF component (Fig. 1a).

In a similar way, t_{pUP} was defined as the time when the centre of mass vertical acceleration decreased to zero and detected as the sample at the intersection between the line representing the subject body weight and the line joining the 20% and 80% of the peak over the last region of positive slope of the vertical force (Fig. 1b). STS duration was then determined as $T_{\mathrm{STS}} = t_{\mathrm{pUP}} - t_{\mathrm{STS}}$.

The detection of t_{UP} was the most challenging, considering that the transition from the pUP to the UP is not as well defined as the other transitions and was expected to occur more gradually than the other transitions. The CoP trajectory reflects the actions of the body that control the movements of the centre of gravity and highlights the balance changes, therefore it was used to detect t_{UP}. In all the experimental conditions, the CoP trajectory was expected to be remarkably less variable during UP than during pUP. In order to effectively compare CoP trajectories, trial data acquisitions were analysed over the same time interval [38]. In this study, it was chosen to analyse 25 s of CoP trajectory starting from t_{STS}. This duration was sufficient to reach a steady upright posture, since the transient component of the CoP signal is contained primarily in the first 20 s of a trial [34].

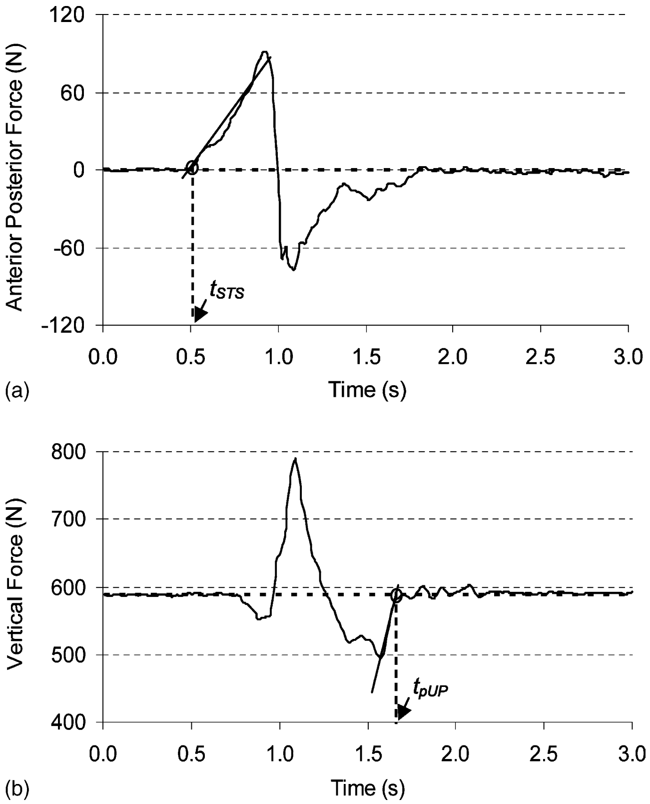

Fig. 1. (a) The procedure used to detect the instant t_{STS} at which the sit-to-stand begins. From the anterior–posterior ground reaction force, the first positive slope of the curve is isolated, and a straight line is used to join 20% and 80% of the curve peak. The instant t_{STS} is the sample at which that line crosses the time axis. (b) Procedure used to detect the instant t_{pUP} at which the preparation for the upright posture begins. From the vertical ground reaction force curve, the last positive slope is isolated, and a straight line is traced to join the 20% and 80% of the curve peak. The instant t_{pUP} is determined as the sample at which this line crosses the line representing the subject body weight (dashed line).

The CoP trajectory was time-windowed with a sliding window of the duration of w seconds, moved with a determined sliding step (ss) time. Within each windowed CoP trajectory, the 95% confidence circle radius was extracted (d_{CC}) [39,40] as a descriptor of the area covered by the CoP within the current time window, and consequently of the amount of movement during STS, pUP and UP. For the windows sliding over the UP phase, the d_{CC} value was expected to be approximately constant and lower than that obtained from windows sliding over both the STS and pUP phases. A typical d_{CC} curve versus progressive time window steps is illustrated in Fig. 2. The d_{CC} curve reaches its

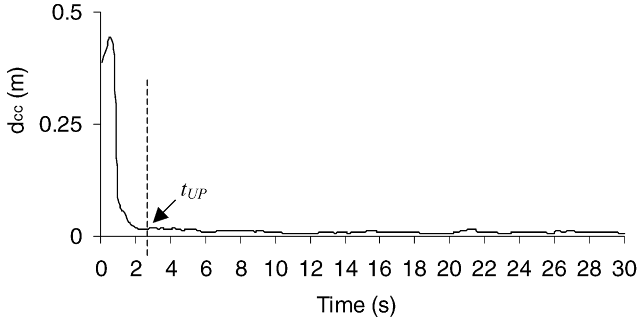

Fig. 2. A typical pattern of the 95% confidence circle radius (d_{CC}) of the windowed CoP trajectory. The time instant t_{UP} representing the beginning of the steady upright posture is also indicated.

maximum value during STS, decreases during the final part of the STS and during pUP and then remains approximately constant during UP. The t_{UP} could then be identified by selecting the ith step of the time window in which the d_{CC}, after reaching the peak during STS, goes below the average value of all the values obtained for the following time windows. This algorithm ensured that all the CoP samples included in the selected window and in the following ones correspond to the UP phase of the trial.

In addition to the d_{CC}, the same windowing procedure was performed on the CoP mean velocity (*mv*) [40], an alternative candidate to effectively describe movement changes during the task execution.

Given the low sensitivity of the algorithms to the *ss* values, a sliding step of 0.1 s was chosen since this value guaranteed a satisfactory time resolution. For both the d_{CC} and mv curves, the duration of the time window w had a great influence on the determination of t_{UP}. For $w < 1$ s, the d_{CC} curve versus progressive time windows consistently showed an irregular pattern, hence reducing the effectiveness of the detection of t_{UP} (Fig. 3a); conversely, for $w > 4$ s, in the region where the t_{UP} was expected, the d_{CC} time history was usually too smooth to allow for the detection of t_{UP} using the same algorithm (Fig. 3b). Similar results were found for the *mv* curves.

To set the duration of the window w for both d_{CC} and *mv*, an intra-subject repeatability study was performed by determining, at different values of w, the value of the variance (also called variation) ratio (VR) [41–43]. The VR values were computed for the four conditions on both the windowed d_{CC} and *mv* curves with w varying between 1 and 4 s (with 1 s intervals). The estimate of VR allowed scoring the window durations. In fact, when a set of trials executed by a single subject is analysed and all trials are considered equivalent, all of the variability shown by the chosen descriptive variable should be caused by the variability with which the subject performs the motor task. If the descriptive variable contains parameters to be set, as in this case, parameters should be set to those values that minimise the variability among the tasks, since any additional variability cannot be related to the variability with which the subject performs the task. As reported in Table 1, both the d_{CC} and *mv* patterns were highly repeatable, with the VR being slightly higher for the d_{CC} curves. Maximum repeatability for the d_{CC} curves was obtained for $w = 2$ and 3 s. The d_{CC} curves with $w = 2$ s were therefore chosen to determine t_{UP}.

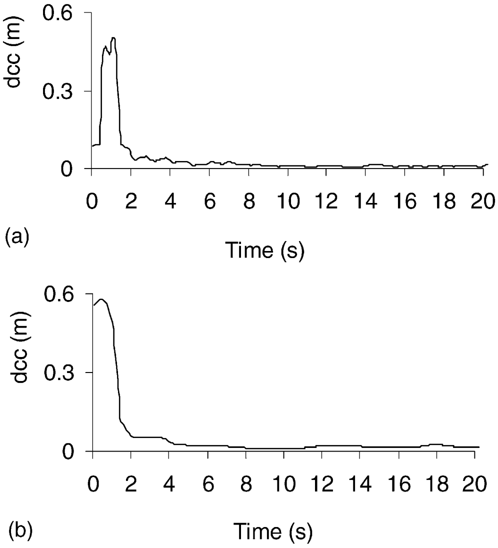

Fig. 3. Patterns of the 95% confidence circle radius (d_{CC}) of the windowed CoP trajectory obtained by using different time windows. A window length $w = 1$ s caused an irregular and unpredictable pattern (a), while a window length $w = 4$ s caused an excessive smoothing of the pattern (b).

Given t_{UP}, the duration T_{pUP} of the pUP phase was determined as $T_{pUP} = t_{UP} - t_{pUP}$.

To determine the presence of statistical differences in the values of both T_{STS} and T_{pUP} among the experimental conditions, a two-way ANOVA with repeated measures

Table 1

Mean values (standard deviations) of the variance ratio (VR) index of the 95% confidence circle radius (d_{CC}) and of the mean velocity (*mv*) patterns of the time-windowed (window duration w) CoP trajectory of 22 able-bodied subjects performing the task in four different experimental conditions

w (s)	VR-d_{CC}				VR-*mv*			
	NFT	HFT	NFA	HFA	NFT	HFT	NFA	HFA
1	0.96 (0.06)	0.97 (0.02)	0.97 (0.02)	0.97 (0.02)	0.94 (0.04)	0.95 (0.03)	0.93 (0.03)	0.96 (0.02)
2	0.97 (0.04)	0.98 (0.02)	0.98 (0.02)	0.98 (0.01)	0.96 (0.02)	0.97 (0.02)	0.97 (0.03)	0.97 (0.02)
3	0.97 (0.04)	0.98 (0.02)	0.98 (0.02)	0.98 (0.01)	0.96 (0.02)	0.97 (0.02)	0.97 (0.02)	0.97 (0.02)
4	0.97 (0.04)	0.97 (0.02)	0.98 (0.02)	0.98 (0.01)	0.97 (0.02)	0.96 (0.02)	0.97 (0.02)	0.97 (0.02)

NFT: natural speed with feet together; HFT: high speed with feet together; NFA: natural speed with feet apart; HFA: high speed with feet apart.

was performed assuming speed (two levels: normal, high) and foot position (two levels: together, apart) values as intra-subject factors. For both T_{STS} and T_{pUP}, this analysis provided the following information:

1) sample mean value and standard deviation;
2) significance ($P < 0.001$) of variation as associated with speed, and foot position;
3) significance ($P < 0.001$) of the interaction between factors.

Factors that were found to cause significant pattern variations defined sub-datasets, on which *post-hoc ANOVA* tests were performed.

Reliability of both T_{STS} and T_{pUP} was assessed using the intra-class correlation coefficients ICC(2, 1) and ICC(2, *k*), with $k = 5$.

3. Results and discussion

The algorithms proposed for the analysis of the STS-to-UP motor task were devised and investigated to validate the feasibility of the methodology herein proposed for mobility limitation assessment. Initially, the algorithms for the detection of the transition phase between STS and UP were devised. According to the literature, it was chosen to use the vertical GRF to determine the end of the STS, i.e. the beginning of the pUP phase, while the parameters relevant to the beginning of the steady UP were set, as described in the methods section, through a sensitivity analysis, that led to the choice of using the d_{CC} curves with $w = 2$ s to determine t_{UP}.

The effectiveness of the algorithm proposed to detect t_{UP} was supported by the fact that it occurred always after t_{pUP}. The two instants were determined using two unrelated algorithms and if either or both algorithms failed, then the time order of the two instants could be reversed, which, of course, cannot occur.

The algorithms implemented for the detection of the STS-to-UP time events were able to detect the transition between the different phases and the changes due to different experimental conditions. In particular, the algorithms provided the expected results when both the dynamic and the static parts of the motor task were changed by modifying the velocity and the foot positioning. Results found for the determination of T_{STS}, reported in Table 2, were consistent with those available in the literature. STS duration varied significantly, from 1.2 s for fast to 2.5 s for slow trials consistently with results found in the literature [22,44], while, as hypothesised, no significant differences associated with the different foot positions were found (Table 3). No interaction between speed and foot position was found. The determination of T_{STS} was quite reliable (ICC(2, 1) and ICC(2, *k*) varying across the four conditions from 0.49 and 0.75, and from 0.88 and 0.94, respectively).

Table 2
Mean values (standard deviation) of the sit-to-stand duration, T_{STS}, and preparation to upright posture duration, T_{pUP} computed over 22 able-bodied subjects

	NFT	HFT	NFA	HFA
T_{STS} (s)	1.6 (0.3)	1.1 (0.1)*	1.6 (0.2)	1.0 (0.1)*
T_{pUP} (s)	2.1 (0.5)	2.2 (0.6)	2.7 (0.5)*	2.7 (0.8)*

Data are reported for four different experimental conditions. NFT: natural speed with feet together; HFT: high speed with feet together; NFA: natural speed with feet apart; HFA: high speed with feet apart.

* Indicate a significant difference ($P < 0.001$) with respect to the normal-speed and feet-together trials.

Table 3
ANOVA analysis for the duration of the STS phase (T_{STS}) values

Source of variation	SS	d.f.	MS	F	P-value	F_{crit}
Velocity	5.66	1	5.66	179.05	<0.001	3.955
Foot position	0.01	1	0.01	0.18	0.6734	3.955
Interaction between factors	0.00	1	0.00	0.13	0.7193	3.955

As expected, the values of T_{pUP} did not change in response to the velocity of execution of the task, but were sensitive to the position of the feet, consistently with the results of other studies [45,46], which proved that the foot position strongly affects postural parameters (and, as a result, also d_{CC} and mv). The T_{pUP} was greater (Table 2) for FA trials than for FT trials, both at normal and high speed. This was due to the fact that CoP dispersion during steady UP was lower in FA trials ($r = 12 \pm 3$ mm for FT trials versus 8 ± 2 mm for FA trials; $P < 0.001$) and, therefore, a longer time was needed to reach the steady level of CoP dispersion, typical of an UP. The ANOVA analysis of T_{pUP} (Table 4) showed no interaction between execution speed and foot position: changes in the STS execution speed did not influence the amount of time needed to reach a stable UP.

Subjects reached the UP very differently from trial to trial. This was made evident by the variability of the CoP trajectory patterns. As a result, the values found for T_{pUP} were characterised by a remarkable overall variability. In particular, the intra-subject variability was comparable to the inter-subject variability. This circumstance negatively affected the reliability of T_{pUP}. As mentioned above, the high intra-subject variability was expected (intra-subject variability of postural parameters has been largely described in the literature [47–50]), and claimed to be ascribed to the learning effects that take place when dealing with repeated trials [48]. Inter-subject variability was explained in terms

Table 4
ANOVA analysis for the duration of the preparation to UP (T_{pUP}) values

Source of variation	SS	d.f.	MS	F	P-value	F_{crit}
Velocity	0.13	1	0.13	0.34	0.5636	3.955
Foot position	6.37	1	6.37	17.01	<0.001	3.955
Interaction between factors	0.01	1	0.01	0.02	0.8803	3.955

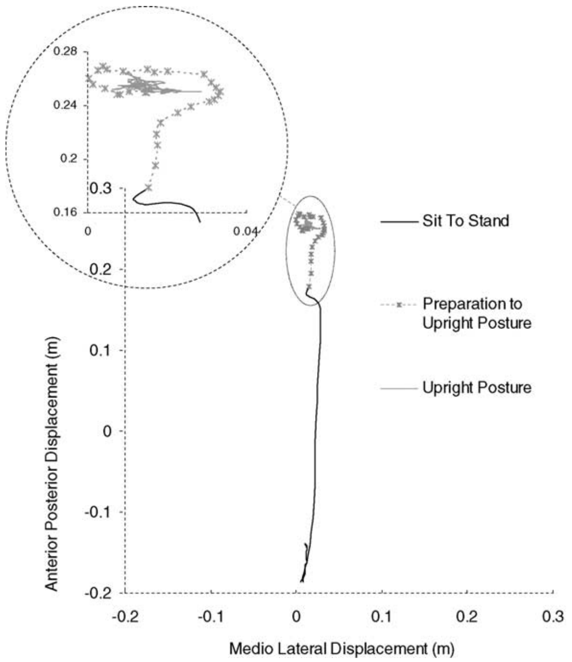

Fig. 4. A typical CoP trajectory during the three phases of the motor task. During the sit-to-stand phase (black line), the CoP displacement takes place mainly in the anterior–posterior direction. After the transitory phase (crossed line), the task ends with the steady upright posture (grey line) during which the CoP displacement is markedly reduced. A magnified and unevenly scaled representation of the final part of the CoP trajectory is depicted in the top left corner to highlight the transitions between the task phases.

of: (a) lack of normative values for stabilometric parameters [49]; (b) intrinsic differences between subjects morphology and muscular functions [50]; and (c) anthropometric and foot placement differences [45]. The low reliability of T_{pUP} does not reduce its relevance nor its usefulness. In fact, the presence of a preparatory phase to the UP is evident both from observing the subject performing the task and from looking at the CoP pattern. By determining its duration, an effective analysis of the characteristics of the isolated phases could be performed. Fig. 4 effectively describes a typical pattern of the CoP trajectory during a STS-to-UP task, divided into the three phases by using the algorithms illustrated earlier.

4. Conclusions

Since the human body is a multi-link system, mechanical redundancies are quite prevalent and are used at neurological level to control postural equilibrium in multi-joint tasks. In order to explain how this redundancy affects postural equilibrium maintenance, it is necessary to identify specific postural patterns and transitions between these patterns. A way to induce changes in postural control was presented in this paper, which is that of reaching the upright position after a sit-to-stand movement. Techniques of analysis of ground reaction forces were developed to detect the time events corresponding to the transition between the different task phases. Such techniques represent a valuable tool for the development of quantitative tests for describing the changes that occur in the balance control system in response to the self-induced perturbation like the one present in the sit-to-stand movement.

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