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Original Article

A novel approach to study human posture control: "principal movements" obtained from a principal component analysis of kinematic marker data

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Abstract

Human upright posture is maintained by postural movements, which can be quantified by "principal movements" (PMs) obtained through a principal component analysis (PCA) of kinematic marker data. The current study expands the concept of "principal movements" in analogy to Newton's mechanics by defining "principal position" (PP), "principal velocity" (PV), and "principal acceleration" (PA) and demonstrates that a linear combination of PPs and PAs determine the center of pressure (COP) variance in upright standing. Twenty-one subjects equipped with 27-markers distributed over all body segments stood on a force plate while their postural movements were recorded using a standard motion tracking system. A PCA calculated on normalized and weighted posture vectors yielded the PPs and their time derivatives, the PVs and PAs. COP variance explained by the PPs and PAs was obtained through a regression analysis. The first 15 PMs quantified 99.3% of the postural variance and explained 99.60% ± 0.22% (mean ± SD) of the anterior-posterior and 98.82 ± 0.74% of the lateral COP variance in the 21 subjects. Calculation of the PMs thus provides a data-driven definition of variables that simultaneously quantify the state of the postural system (PPs and PVs) and the activity of the neuro-muscular controller (PAs). Since the definition of PPs and PAs is consistent with Newton's mechanics, these variables facilitate studying how mechanical variables, such as the COP motion, are governed by the postural control system.

Key words: human movement; motor control; stability; balance; principal component analysis PCA; principal movements; center of pressure COP.

Introduction

The human body is a multi-segmental mechanical system whose inter-segment movements are generated and modified by actuators (muscles) controlled by a complex neuronal network. How this system achieves and maintains postural stability has been an important question in biomechanics and neuroscience over many decades.

The center of pressure (COP) excursion is a frequently used variable to assess balance and stability in humans. The COP offers a direct measure of mechanical stability in the sense that a COP position too close to the border of the base of support indicates an instability that must be corrected in order to prevent a fall. Furthermore, the characteristics of the COP motion provide information about the neuro-muscular control, particularly in cases of neuro-muscular deficits, for example, cerebral palsy (Donker et al., 2008; Rose et al., 2002), stroke (Corriveau et al., 2004; Roerdink et al., 2006), concussion (Cavanaugh et al., 2005; Cavanaugh et al., 2006; Rubin et al., 1995), or frailty (Lipsitz, 2002) and fall risk (Maki et al., 1994) in the elderly.

How postural movements govern the COP has been described for the inverted pendulum model (Winter et al., 1996; Winter et al., 1993). In this model the COP motion is determined by two aspects. First, the COP position depends on the position of the center of mass (CM) – if the body sways forward, then the COP will also move forward. Second, the COP depends on the acceleration of the body – when leaning forward, the neuro-muscular postural control system needs to produce a moment of force that pushes the body back into an upright position. This moment is created by muscle action moving the COP further forward. Hence, even in this simplified model a forward motion of the COP can be caused by either a forward sway or a backward acceleration of the body. In actual postural movements the COP motion is additionally influenced by other motion patterns such as hip-, knee, or upper body strategies (Hsu et al., 2007; Pinter et al., 2008), physiologic movements such as breathing (Hodges et al., 2002), and movements triggered by cognitive processes such as arousal level (Maki and McLlroy, 1996) or emotional state (Hillman et al., 2004).

The neuro-muscular control of the COP motion has been analysed by correlating magnitudes of muscle synergies [M-modes (Krishnamoorthy et al., 2003a)] with changes in COP position. Muscle synergies are calculated by performing a principal component analysis (PCA) on normalized electromyographic (EMG) data obtained from several muscles. For voluntary postural sway, M-modes explained 71% (Klous et al., 2011) and 88% (Krishnamoorthy et al., 2003b) of COP variance, however, explained variance dropped markedly when sway frequency was increased (Danna-dos-Santos et al., 2007).

Kinematic synergies obtained from performing a PCA on, for example, joint angles (Alexandrov et al., 1998; Freitas et al., 2006; Tricon et al., 2007; Vernazza et al., 1996) or marker coordinates (Federolf et al., 2013a; Federolf et al., 2012b), were also used to study aspects of postural control. When applied to marker coordinates, the PCA transforms the complex, high-dimensional movements of all markers into a set of one-dimensional movement components. These PCA-generated movement components have been called "principal movements" (PMs) (Eskofier et al., 2013; Federolf et al., 2014; Federolf et al., 2012b; Maurer et al., 2012). To date, kinematic synergies or PMs are usually considered as theoretical constructs that relate to, but that do not directly quantify the mechanics of the postural control system.

The purposes of the current paper are to define postural PMs consistent with Newton's mechanics; to validate that these PMs represent the mechanics of human postural motion by testing the hypothesis that a linear combination of PMs explain the COP variance; and to outline implications of this methodologic approach for postural control research.

Methods

Participants

Twenty-one volunteers (11 males, 10 females, age 26.4±2.4, height 176±8 cm, weight 71±10 kg [mean ± standard deviation]) with good self-reported general health and no recent injury or other condition that that could affect balance were recruited. All subjects provided written informed consent prior to participating and the study protocol was approved by the Norwegian Regional Ethical Committee.

Measurement procedures

Measurements started with the volunteers standing in front of the force plate. The subjects were instructed to step onto the force plate into a comfortable, hip-wide, bipedal stance upon a signal from the experimenter. Then the subjects stood on the force plate with their hands on their hips until the experimenter signaled that the measurement was complete. For each subject, 1 trial of 2 minute duration was collected. Subjects were not explicitly required to “stand as quiet as possible,” however, they were asked to avoid any movements not required for postural control such as scratching or turning the head.

Instrumentation

The volunteers were equipped with 27 retro-reflective markers placed on the participant’s head (3 markers on a custom-build adjustable helmet), C7, manubrium, and placed bilaterally on the acromion, lateral epicondyle, dorsal side of the wrist joint, crista iliaca, trochanter major, thigh, lateral femoral condyles, tibial shaft, lateral malleoli, posterior on the calcaneum, and on the 1st metatarsophalangeal joint. The positions of these markers were sampled at 300 Hz using a motion tracing system consisting of 10 Oqus 400 cameras (Qualisys, Gothenburg, Sweden). The ground reaction forces were recorded at 1500 Hz using an AMTI Optima force plate (AMTI, Watertown, MA, USA). The cameras and the force plate were controlled by a computer running the software Qualisys Track Manager (Qualisys, Gothenburg, Sweden), which synchronized the data acquisition devices and calculated the 3D positions of the markers and the COP position. All further data processing and analyses were conducted in Matlab (The MathWorks Inc., Natick, MA, USA). The data from one minute standing on the force plate, from second 20 to second 80, was selected and the COP data was down-sampled to 300 Hz.

Normalization of the data

In analogy to previous studies (Daffertshofer et al., 2004; Federolf et al., 2012a; Troje, 2002; Verrel et al., 2009), the current study interpreted the 3D coordinates (x,y,z) of all markers at a given time t as a posture vector

$$\mathbf{p}(t) = [\ x_1(t), y_1(t), z_1(t), x_2(t), \ldots, y_j(t), z_j(t)\ ] \tag{1}$$

where j is the number of markers (j=27 in the current study). [Notation: bold printed, small-letter variables represent vectors; bold printed, capital-letter variables represent matrices; normally printed variables represent scalars; a bar over a variable indicates the mean over time.]

The normalization procedure applied to these posture vectors was designed to allow pooling the posture vectors of all subjects into one matrix M such that (i) every subject contributes an equal share to the variance in M, (ii) the influence of anthropometric differences on the variance in M is minimized, (iii) the relative amplitude of the marker motion is preserved, (iv) the fraction of body weight that each marker represents is adequately represented. Pooling the data of all subjects into one matrix has the advantage that results can be directly compared between subjects. Thereto the following steps were conducted: (1) For each subject, subj, a mean posture vector $\overline{\mathbf{p}^{subj}} = [\overline{x_1(t)}, \overline{y_1(t)}, \ldots, \overline{z_j(t)}]$ was subtracted from each posture vector:

$$\mathbf{p}'(t) = \mathbf{p}(t) - \overline{\mathbf{p}^{subj}} \tag{2}$$

Thus, the PCA was conducted on deviations from a subject's mean posture, i.e. on postural movements, not on the postures themselves. This procedure is a first step towards removing anthropometric differences.

(2) For each subject the postural movement vectors p'(t) were divided by their mean Euclidian norm $\overline{d^{subj}} = \overline{\|p'(t)\|_2}$ (Federolf, Roos, Nigg, 2013):

$$p''(t) = {}^{1}\!/_{\overline{d^{subj}}}\; p'(t) \tag{3}$$

This normalization step ensures that each subject contributes the same variance to the pooled matrix M and minimizes amplitude differences due to subjects' anthropometric differences.

(3) Finally, for each marker i a weight factor w_i was defined according to the relative body mass that this marker represented. Specifically, w_i was calculated by dividing the relative weight of the segment to which the marker was attached, m_s, by the number n_s of markers on this segment. For markers placed on joints, the masses of both segments were added. For example, w_i for the knee markers was calculated as $w_i = m_{thigh} / n_{thigh} + m_{shin} / n_{shin}$ with $n_{thigh} = n_{shin} = 3$, $m_{thigh} = 14.16\%$, and $m_{shin} = 4.33\%$ for men and $m_{thigh} = 14.78\%$ and $m_{shin} = 4.81\%$ (De Leva, 1996). Thus, the normalized postural movement vectors had the form

$$p'''(t) = \frac{1}{\overline{d^{subj}}} \; [\, w_1 \cdot \left(x_1(t) - \overline{x_1(t)}\right), w_1 \cdot \left(y_1(t) - \overline{y_1(t)}\right), \ldots, w_j \cdot \left(z_j(t) - \overline{z_j(t)}\right)]. \tag{4}$$

Principal component analysis and kinematics in posture space

The normalized p'''(t) of all participants were concatenated into a 378,000 x 81-matrix M (participants(21) * trial duration(1min) * measurement frequency(300 Hz) x number of markers(27) * 3D; i.e. observations x dimensions), which was then submitted to a PCA. The PCA has three types of results (Daffertshofer et al., 2004; Troje, 2002): a set of orthogonal eigenvectors v_k, a set of associated eigenvalues ev_k, and, for each participant, a set of time series $\xi_k^{subj}(t)$ obtained by projecting the normalized postural movement vectors p'''(t) onto the eigenvectors v_k.

The whole set of eigenvectors $\{v_k\}$ form an orthonormal basis in the vector space of postural movements. Each eigenvector v_k represents a specific postural movement pattern where the vector components in v_k describe how the movements of the individual markers are correlated with the movements of the other markers (Federolf, 2013; Federolf et al., 2013b). The scores $\xi_k^{subj}(t)$ quantify the subject's postural movements according to the motion patterns defined by the associated v_k (Daffertshofer et al., 2004). The vectors v_k have been referred to as principal movements (PM) (Federolf et al., 2012b). However, to define the PMs consistent with Newton's mechanics, the following new variables are introduced: the amplitude of the PM_k that a subject subj shows at time t is given by the scores $\xi_k^{subj}(t)$. In other words, the scores $\xi_k^{subj}(t)$ quantify a position in posture space (i.e. how much the posture at time t deviates from the mean posture in direction of v_k). The $\xi_k^{subj}(t)$ could thus be referred to as "principal position" (PP_k). The rate at which a postural configuration changes can then be quantified by the principal velocity (PV_k), given as the first time derivative $\frac{d}{dt}\xi_k^{subj}(t)$ of PP_k. The acceleration of postural movements can be quantified by principal accelerations (PA_k), calculated as the second time derivative $\frac{d^2}{dt^2}\xi_k^{subj}(t)$ of PP_k. Since all v_k are linear combinations of the original marker coordinates, the definitions of the PP, PV and PAs is consistent with standard differentiation rules and the laws of Newton's mechanics. In the current study, an additional filtering of the PPs with a Butterworth filter (5th order, 2Hz low-pass) was necessary before calculating PVs and PAs to reduce the effects of the noise amplification in the differentiation process.

A graphical representation of the PMs (animated stick figures) can be created by expressing the PMs as vectors pm(t) in the original vector space, i.e. by selecting individual components k and retracing the normalization steps:

$$\boldsymbol{pm_k^{subj}(t)} = \overline{\boldsymbol{p^{subj}}} + \boldsymbol{a}\ \overline{\boldsymbol{d^{subj}}}\, \boldsymbol{W^{-1}}\, \boldsymbol{\xi_k^{subj}(t) \cdot v_k} \tag{5}$$

The factor a introduced in this equation can be used to artificially amplify the motion amplitude. The matrix W represents a diagonal matrix with the weight factors w_i on the diagonal. The graphical representation allows to interpret the movement components, for example, previous research has shown that for quiet standing the first few PMs closely represent ankle-, hip-, and higher-order postural strategies (Federolf et al., 2013a; Federolf et al., 2012b).

Relationship between PMs and CoP motion

The COP is defined as the point of application of the ground reaction force (GRF), which is the reaction force to gravity and to inertial forces produced by accelerations of the body or its segments. In quiet standing the accelerations are predominantly produced by resultant muscle forces. The COP position is thus determined by the subject's posture (defining the mass distribution and thus the gravitational forces), and postural accelerations (relating to inertial / muscle forces). In other words, the COP position should be a linear combination of PPs and PAs (but not PVs):

$$\boldsymbol{COP_{l,x/y}^{subj}(t)} = \sum_{\boldsymbol{k=1}}^{\boldsymbol{l}} \left(\boldsymbol{cp_{k,x/y}^{subj}\, \xi_k^{subj}(t)} + \boldsymbol{ca_{k,x/y}^{subj}}\, \frac{\boldsymbol{d^2}}{\boldsymbol{dt^2}} \boldsymbol{\xi_k^{subj}(t)} \right) \tag{6}$$

The coefficients cp_k and ca_k quantify the contribution of the k-th PP and PA to the COP motion, respectively. Since for increasing indices k the PM_k quantify decreasing amounts of postural variance (ev_k decrease with increasing k), an upper limit l may be defined to limit the number of PMs considered in the analysis. In the current study, l = 15 was chosen. However, the impact of higher-order PMs on the COP variance was also evaluated as they may also contain relevant information (Maurer et al., 2012; Nigg et al., 2012).

The coefficients cp_k and ca_k were determined by first centering the anterior-posterior (x) and the medio-lateral (y) components of the measured COP motion, ${}^{measured}\boldsymbol{COP}_{x/y}^{subj}(\boldsymbol{t})$, and then performing a regression analysis to solve the following equation:

$$ {}^{\mathrm{measured}}\mathrm{COP}_{\mathrm{x/y}}^{\mathrm{subj}}(\mathrm{t}) = \sum_{\mathrm{k}=1}^{\mathrm{l}} \left(\mathrm{cp}_{\mathrm{k,x/y}}^{\mathrm{subj}}\, \xi_{\mathrm{k}}^{\mathrm{subj}}(\mathrm{t}) + \mathrm{ca}_{\mathrm{k,x/y}}^{\mathrm{subj}} \frac{\mathrm{d}^2}{\mathrm{dt}^2} \xi_{\mathrm{k}}^{\mathrm{subj}}(\mathrm{t}) \right) + \mathrm{R}_{\mathrm{l,x/y}}^{\mathrm{subj}}(\mathrm{t}) \qquad (7) $$

The residua $\mathrm{R}_{\mathrm{l,x/y}}^{\mathrm{subj}}(\mathrm{t})$ are a measure of how much of the measured COP variance can be explained by the first l PMs (expressed as percent):

$$ \mathrm{Var}_{\mathrm{l,x/y}}^{\mathrm{subj}} = \left(1 - \sum_{\mathrm{t}} \left(\mathrm{R}_{\mathrm{l,x/y}}^{\mathrm{subj}}(\mathrm{t}) \right)^2 / \sum_{\mathrm{t}} \left(\mathrm{COP}_{\mathrm{x/y}}^{\mathrm{subj}}(\mathrm{t}) \right)^2 \right) * 100 \qquad (8) $$

The square root of $\mathrm{Var}_{\mathrm{l,x/y}}^{\mathrm{subj}}$ (equation 8) is equal to the Pearson correlation coefficient between calculated (equation 6) and measured COP motion.

Sensitivity analysis

A leave-one-out cross validation was conducted consecutively using all subjects. The data of the selected subject was removed from the PCA input to obtain PC-vectors independent from the selected subject's data. The leave-one-out PC-vectors were compared with the all-subject PC-vectors by calculating their dot product. Then PP_k and PA_k were calculated by projecting the selected subject's data onto the leave-one-out PC-vectors to calculate how much of the selected subject's COP variance could be explained.

Results

Characterization of the first 15 principal movements

The eigenvalues and an interpretation of what aspect of the whole motion each of the first 15 PMs represented is given in Table 1. Together these 15 PMs quantified 99.3% of the postural variance. For the first 4 PMs, a visual representation of the changes in posture and of the PP_k and PA_k time series is shown in Figure 1.

Qualitatively, the following movement components can be distinguished (Table 1): PM_1, PM_2, PM_3, and PM_5 closely represented postural control movements that are usually described as ankle- and hip strategy (Figure 1, first, second and third row). PM_4, PM_6, PM_8 and PM_9 could be associated with breathing, for example, indicated by a rise of the shoulders and a visible breathing rhythm in the PP_k time series (Figure 1, fourth row). PM_6, PM_7, PM_8, PM_{10}, PM_{11}, PM_{13}, PM_{14}, and PM_{15} were influenced by various forms of head movements associated with different compensatory movements in the body. PM_7 and PM_9 showed rotations of the pelvis around a vertical axis.

COP variance explained by PMs

In all 21 subjects the first 15 PMs explained 99.60 ± 0.22% (mean ± SD; range: 98.99% - 99.94%) of the anterior-posterior and 98.82 ± 0.74% (range: 97.32% - 99.75%) of the lateral COP variance. Figure 2 visualizes how explained variance depend on the number l of PMs considered in the regression. In both COP components including the ankle and hip strategies (PM_1 and PM_3 in anterior-posterior; and PM_2 and PM_5 in lateral direction) substantially improved the regression accuracy. This suggests that these strategies dominate the COP excursion. However, considering further PMs and PAs in the regression marginally, but consistently improved the explained COP variance in all subjects (tested up to l =50).

Sensitivity analysis

The first 15 PC-vectors were similar whether or not one subject was removed from the PCA calculation: the dot-product results (absolute values) ranged from 0.9999 ± 0.0001 for PC1 to 0.88 ± 0.24 for PC15 (mean ± standard deviation). The COP variance of the subject removed from the PCA calculation could, on average, be explained with a precision of 99.59 ± 0.22 % and 98.79 ± 0.75 % in anterior-posterior and in lateral direction, respectively.

Discussion

The most important novelty of the current paper is the formulation of kinematics in posture space, which is made possible by factoring in the relative mass that each marker represents in the normalization of the posture vectors. The resultant PMs explained COP variance with better precision (>97%) than previous methods (71-88%) (Danna-dos-Santos et al., 2007; Klous et al., 2011; Krishnamoorthy et al., 2003b). This is important for postural control research, since the PMs directly link the behaviour of the person to the COP motion – a variable often assessed in the context of postural stability or abnormal postural control. The sensitivity analysis demonstrated the stability of the PC-vectors and the effectiveness of the normalization procedure.

Interventions of the postural control system, for instance to correct extreme COP positions, are facilitated through the actuators in the system, i.e. the muscles. Muscle activation produces either a stiffening of the system (co-contraction) or relative accelerations between body segments. The combination of the activation patterns of different muscles (muscle synergies) control or produce between-segment accelerations that change a subject’s posture. This, the between-segment accelerations changing the subject’s posture, is exactly what the PAs quantify. In other words, PAs can be seen as neuro-muscular control patterns. Unlike

EMG-based measures of neuro-muscular control, which rely on punctual measurements of the electrical input to some muscles, the PAs characterize muscle activation patterns based on the combined mechanical output of all muscles in the system. Calculation of the PMs thus provides novel variables that simultaneously quantify the state of the system (PPs and PVs) and the activity of the neuro-muscular controller (PAs).

Since the definition of PPs and PAs is consistent with Newton's mechanics, these variables facilitate studying how mechanical variables, such as the COP motion, are governed by the postural control system. To give a concrete example: Figure 3 shows a measured medio-lateral COP excursion (lower left corner) and an almost congruent COP motion calculated from equation 6 (lower right corner). The two dominant postural control strategies, the ankle (PM_2) and hip strategy (PM_5), are shown in the top and middle rows of Figure 3, respectively. The COP motion shows a positive peak at 16.1s and a negative peak at 6.3s. The PP graphs show that in both cases the subject was leaning towards these directions in the moment of the COP peak (PP_2 graph), however, the peak itself is associated with different activity of the postural control system: the negative peak coincides with an acceleration of the ankle strategy (PA_2), the positive peak with an acceleration of the hip strategy (PA_5).

Quantifying postural control through a set of PMs also represents a paradigm shift compared to many current approaches in postural control research: to date, most studies are based on preconceived models of postural control (e.g. the inverted pendulum or double-inverted pendulum model). In contrast, the results of the current study are purely data-driven. The observation that some PMs represent, in good approximation, the classical postural control strategies is a result, not a preconceived postulation. Furthermore, by calculating the PMs, the interrelation between postural control movements, physiological movements (e.g. breathing) and movements that may serve other purposes (e.g. head motion) can be studied. In fact, the eigenvalues observed in the current study show that a breathing movement (PM_4) contributed more to postural variability than the medio-lateral hip strategy (PM_5). In agreement with previous studies, the current study also demonstrated that breathing (Hodges et al., 2002), head movements (Bonnet and Despretz, 2012; Schärli et al., 2013) and other higher-order movement components (Hsu et al., 2007; Pinter et al., 2008) have a measurable effect on the COP excursion. The observation that higher-order PMs up to l =50 still improved the regression result suggests that even these marginal movement components are still mechanically relevant. Thus, in a way, calculating PMs can be seen as constructing a data-driven model for the mechanics of the postural control system, whose precision can be freely chosen based on cumulated eigenvalues or on explained COP variance.

Limitations

It should be noted that the qualitative descriptions of the PMs (Table 1) are interpretations of what movement aspect seemed to dominate each PM. However, none of the PMs is a “pure” representation of only that aspect. In fact, all PMs are linearized, one-dimensional components of motion, hence, individually they do not represent movements that a person could actually carry out. The PMs provide – and should be interpreted as – a coordinate system of movement components, not as actual movements.

A sex-specific, but otherwise standard mass distribution was applied to the data of all subjects. Especially when applying the suggested analysis method to populations whose characteristics differ from the standard body mass distribution, measurement and implementation of the individual mass distributions might improve the results.

A low-pass filter (2Hz) was applied to the PP-time series before calculating the PVs and PAs to reduce noise amplification in the differentiation process. Frequency components in the COP higher than the cut-off frequency can thus not be adequately represented by PVs or PAs. A recent spectral analysis suggested that some information may be lost for cut-off frequencies below 10Hz (Salavati et al., 2009), however, the high explained COP variances observed in the current study suggest that loss of information due to filtering was marginal.

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Conflict of Interest Statement

I declare that I am not aware of any potential or actual conflicts of interest concerning the manuscript.

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Tables

Table 1 Eigenvalues ev_k and qualitative characterization of the first 15 PMs

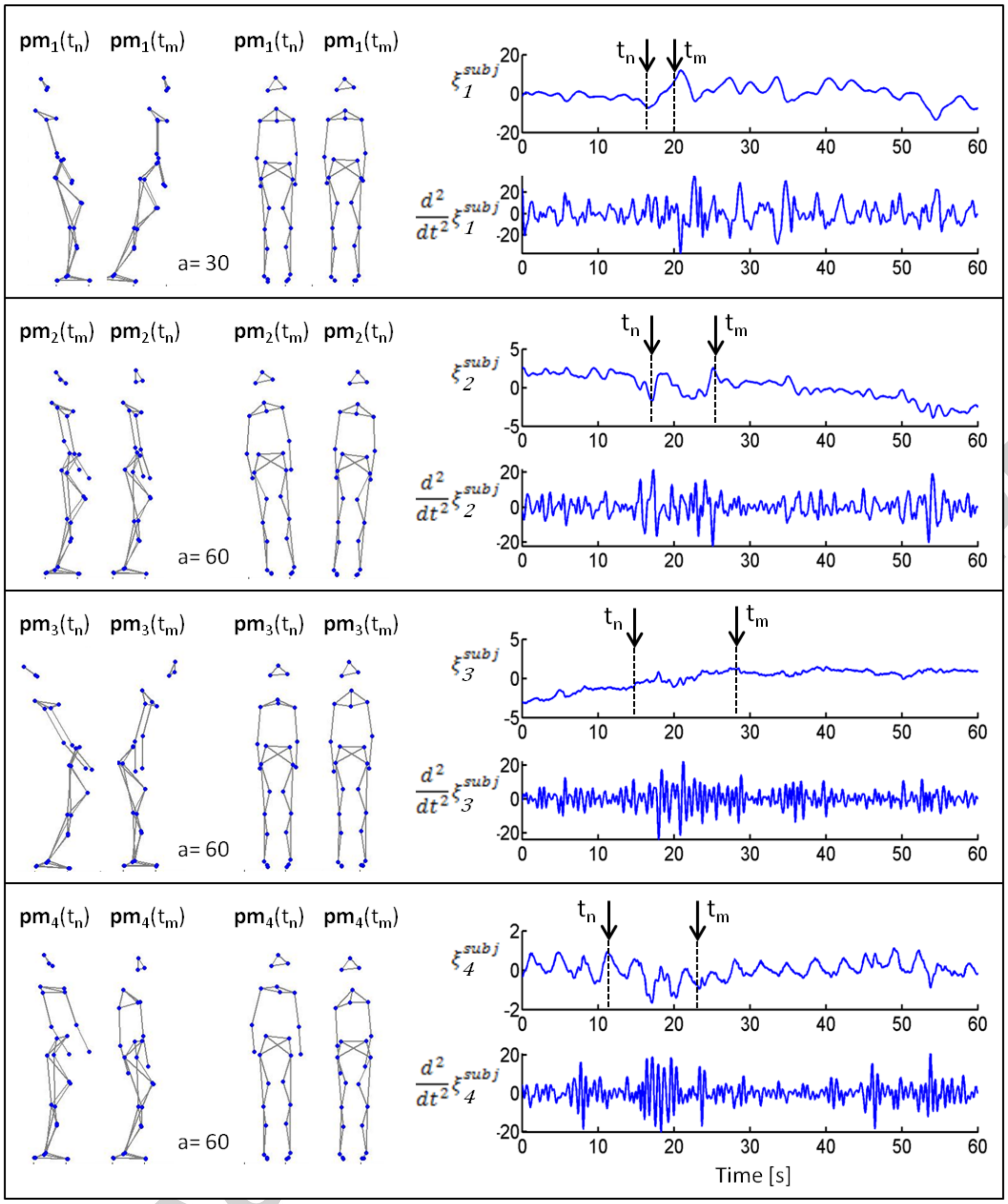
k	eigenvalue ev_k [%]	Interpretation of the movement component based on animated representations of $pm_k(t)$ (equation 5) [ap = anterior-posterior; ml = medio-lateral]
1	75.2	Sagital plane sway around the ankle joint (ap ankle strategy)
2	11.8	Frontal plane shift of the body (ml ankle strategy)
3	5.3	Anterior-posterior hip strategy
4	1.9	Breathing: rhythmical rise and lowering of shoulder belt coupled with a slight rotation of the trunk
5	1.7	Frontal plane trunk rotation (ml hip strategy)
6	1.2	Breathing: rhythmical rise and lowering of shoulder belt and arms coupled with an ap motion of the head
7	0.53	Transversal plane rotation of the pelvis coupled with asymmetrical flexion in the knee joints and with a small-amplitude ap head motion
8	0.43	Knee flexion-extension coupled with breathing-related shoulder and head movements
9	0.38	Transversal plane rotation of the hip, coupled with asymmetrical flexion in the knee joints; breathing motion in the shoulder belt
10	0.26	Ap and ml inclination of the head with compensatory motions in the body, particularly in one arm
11	0.21	Inclination and turning of the head with compensatory motions in the body, particularly in both arms
12	0.18	Asymmetrical vertical shoulder and arm motion
13	0.12	Turning of the head with compensatory motion in the shoulders and pelvis
14	0.097	Small-amplitude head turning coupled with a pelvis rotation
15	0.082	Small-amplitude head turning coupled with asymmetrical flexion in the knee joints

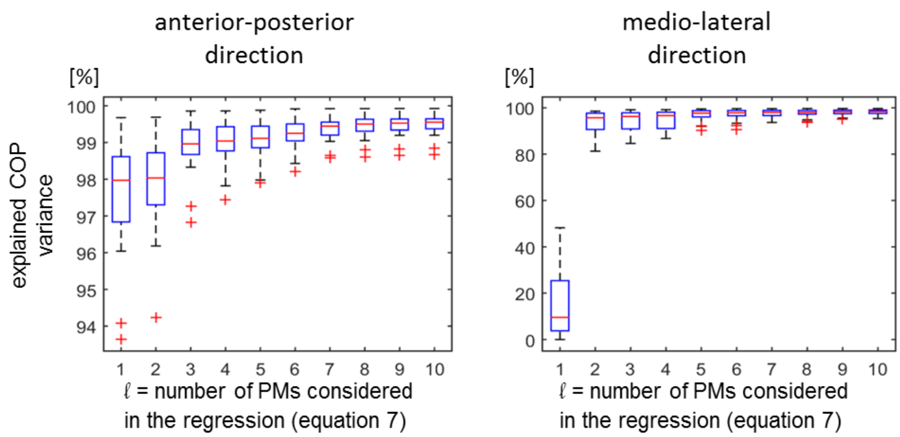
Figure captions

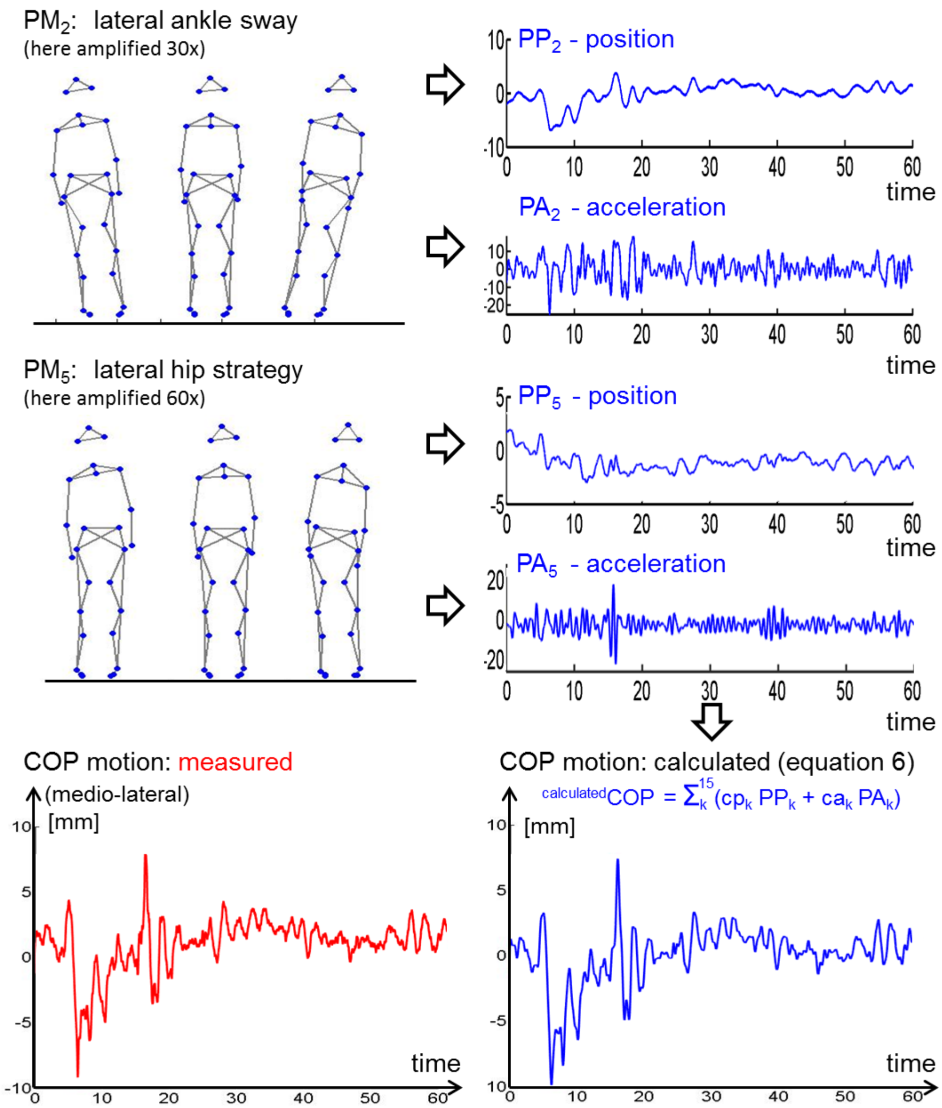
Figure 1 Visualization of the postural changes and the time evolution according to the first 4 principal movements (PM) in upright standing. One subject was selected for this visualization. For each PM, two time points t_n and t_m were selected where the PM had a positive or negative amplitude, respectively. The first column shows a sagittal view, the second column a frontal view of the subject`s posture at t_n and t_m. To make the postural changes visible, they had to be amplified by a factor a as defined in equation 5 (a=30 for PM_1; a=60 for PM_{2-4}). The third column displays the time evolutions $\xi_k^{subj}(t)$ and $\frac{d^2}{dt^2}\xi_k^{subj}(t)$ of the principal position (top) and of the principal acceleration (bottom), respectively. The two selected time points t_n and t_m are indicated in the principal position graph.

Figure 2 COP variance explained by the PMs in the anterior-posterior (left) and lateral (right) direction for the 21 subjects displayed as a function of the number l of PMs considered in the analysis. For better clarity only l = 1 to 10 are displayed.

Figure 3 Measured lateral COP excursion in one selected trial (bottom left graph) and COP motion calculated from the first 15 PMs determined for this subject (bottom right graph). The PP- and PA-time series representing the ankle and hip strategies are displayed in the top and middle rows. Many features of the COP evolution can be recognized in the PP and PA time series. For example, the spike in the COP motion at 16.1 s seems to be caused by a combination of the subject leaning in this direction (PP_2: ankle strategy) and a rapid acceleration of the upper body (PA_5: hip strategy). The two negative spikes at 6.3 s and 8.1 s seem to be caused by the subject leaning in the other direction (PP_2) combined with ankle-strategy accelerations (PA_2).


pm1(tn) pm1(tm) pm1(tn) pm1(tm)
a= 30
pm2(tm) pm2(tn) pm2(tm) pm2(tn)
a= 60
pm3(tn) pm3(tm) pm3(tn) pm3(tm)
a= 60
pm4(tn) pm4(tm) pm4(tn) pm4(tm)
a= 60
tn
tm
Time [s]


anterior-posterior direction
medio-lateral direction
[%]
explained COP variance
100
99
98
97
96
95
94
80
60
40
20
0
1 2 3 4 5 6 7 8 9 10
ℓ = number of PMs considered in the regression (equation 7)



PM2: lateral ankle sway
(here amplified 30x)
PP2 - position
PA2 - acceleration
PM5: lateral hip strategy
(here amplified 60x)
PP5 - position
PA5 - acceleration
time
COP motion: measured
(medio-lateral)
[mm]
COP motion: calculated (equation 6)
calculatedCOP = Σk15 (cpk PPk + cak PAk)
[mm]
time