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Application of Supervised Principal Motion Analysis to Evaluate Subjectively Easy Sit-to-Stand Motion of Healthy People

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ABSTRACT Redundant human motions such as walking or sit-to-stand motions involve time-series data of several variables. Principal motion analysis (PMA) can be adopted to decompose such motions into independent motions, and their linear combinations can be used to approximate the motions. In contrast to the existing PMA methods, which are unsupervised, we applied partial least-squares regression to perform PMA such that the scores for the principal motions were correlated with a continuous objective variable. To validate the practicality of this approach, we investigated the subjectively easy sit-to-stand movement of healthy people. The participants were six healthy young individuals who performed the sit-to-stand movement under 33 different conditions by changing the foot position, hand-grip position, and initial pitch angle of the upper body. The motion data and magnitude of the subjective burden reported for each movement were analyzed. Three principal motions correlated with the subjective burdens were determined and interpreted. The correlation coefficients of the first, second, and third principal motions and the subjective burdens were 0.60, 0.27, and 0.19, respectively. Moreover, the sit-to-stand conditions synthesized by the three principal motions incurred a burden subjectively smaller than or comparable to the burdens in other conditions.

INDEX TERMS Motion synergy, foot position, handrail grip position, subjective burden, supervised learning.

I. INTRODUCTION

By analyzing human motions, certain recommendations can be suggested, for example, to ease motion-related pain and reduce the energy consumption. Human motion is dynamic and involves multiple joints; hence, instead of the principal component analysis (PCA), principal motion analysis (PMA)[1] is used to analyze this motion [1]–[5]. Similar to PCA, PMA reduces the dimensions of the parameter spaces without losing the information of the dynamically interlocked multiple degrees of freedom of redundant systems. The set of the correlated time-series of these multiple degrees of freedom is termed as the principal motion or motion synergy. Any sampled motion can be approximated by the linear combinations of several principal motions when the sample set fits the space, with the scores of the principal motions corresponding to the base. In other words, PMA represents the time-extension of the PCA, and it is an unsupervised method.

In contrast, generalized PMA is a supervised method based on the categories of samples [6]. In this method, the principal motions are identified by classifying samples according to their categories. Specifically, this approach represents the time-extension of the linear discriminant analysis method. However, the generalized PMA does not allow the use of continuous variables as objective variables to supervise the analysis. To ensure the use of continuous objective variables, we aimed to establish a PMA approach based on the partial least-squares regression (PLS), which determines the principal motions whose scores are correlated with the continuous objective variables. To the best of our knowledge, such an extended PMA method has not yet been employed to analyze human motions.

[1]Several names have been used for the family of PMA techniques, including spectrum analysis, synergy analysis, motion primitives, and functional PCA.

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We apply the PMA method extended by PLS on sit-to-stand movements, with the subjectively reported magnitude of burden as the objective value. As summarized in Section II, numerous studies have investigated methods to reduce the physical burden on the lower limbs during sit-to-stand movements [7]. These studies primarily discussed the influence of the environment and posture parameters on the lower-limb joint moments and biomechanical indices but did not focus on the subjective burden pertaining to sit-to-stand motions.

Furthermore, as discussed in Section II, many researchers have focused on the moments of certain joints; however, the subjective burden of the complete body is determined by the synergy of the burdens of multiple joints, not by a certain lower-limb joint [8]. Few researchers have focused on the relationship between the magnitude of the subjective burden and temporal evolution or motion of multiple joint angles and moments during the sit-to-stand movement.

Therefore, in this study, we introduced a supervised PMA that computes the principal motions such that their scores are correlated with a continuous objective variable. Then, its applicability in examining the human motions was investigated considering the analysis of subjectively easy sit-to-stand movements. As mentioned previously, the time-series analyses of sit-to-stand motions have yet to be performed from the viewpoint of subjective burdens. We identified several principal motions correlated with the magnitude of subjective burden and investigated the sit-to-stand movements with a small subjective burden. This study was approved by the institutional review board of the School of Engineering, Nagoya University (#18-2).

II. RELATED STUDIES

Thus far, many researchers have applied unsupervised PMAs on human gaits [1], [3], [4], [6], [9] and found their redundancies, synergies of multiple joints and muscles, and elementary components. PMAs can be also used for other types of human motions [2], [5], [10]–[13]. For example, Yamada *et al.* analyzed the properties of therapeutic techniques of physical therapists based on their manual motions and forces applied to the patients' diseased body parts [13]. As mentioned previously, the present study used a supervised PMA whereas these earlier studies leveraged unsupervised ones.

Many studies reported that the physical burden of sit-to-stand motions can be reduced by ensuring more optimal apparatus settings of parameters such as the height of a chair, and the shape, position, and type of handrails [14]–[26]. Some researchers examined the effects of unilateral handrail use on the lower-limb joint moments [19], [20]. Katuhira *et al.* investigated the influence of different handrail grip positions on both upper- and lower-limb joint moments [23]. In general, the initial knee flexion angle and foot position are critical parameters influencing the lower-limb joint moments [24], [25]. Shepherd *et al.* reported that the initial tilt angle of the upper body affects the duration of occurrence of the maximum moment [26]. Moreover, by using the momentum generated by the upper body, efficient sit-to-stand movements can be performed [27], [28]. These studies focused on physical burdens comprising the lower-limb joint moments and biomechanical indices whereas the present study discusses the subjective burden of sit-to-stand motions.

For the analysis of sit-to-stand motions, the moments of certain joints are particularly studied, which may be partly because pain pertaining to joint diseases such as knee osteoarthritis is linked with joint burdens such as the moments [29], [30]. Further, in the context of low-back pain, the compressive force applied to the lumbar spine, which is usually computed based on the hip moments, is used as a safety standard for industrial workers [31], [32]. However, the subjective burden of the complete body is collectively determined by the burdens of multiple joints. For example, Chihara *et al.* investigated the optimal height and distance of handrails by considering the surface electromyograms of four muscles during sit-to-stand movements [8]. The authors noted that the combination of the electromyogram values of multiple muscles could more accurately predict the subjective impressions compared to that obtained considering a single muscle. In contrast, the present study computed the concurrent changes in multiple joint angles and moments.

Some researchers attempted to optimize the motions of multiple joints during the sit-to-stand motion through optimal control and machine learning [33]–[35]. For example, Mombaur determined the lower-limb joint torques and motions such that the sum of the squared joint torques was minimized [33]. Jamali *et al.* used reinforcement learning to minimize the energies of lower-limb joints required to perform stand-up motion [34]. Similarly, the motions involving the least power consumption were identified using genetic algorithms [35]. Furthermore, several studies indicated that sit-to-stand motions are generated while ensuring reduced muscle outputs. Specifically, the motions may be yielded to reduce the changes in muscle torques [36], [37] or the cost values involving the magnitudes of the muscle torques and their changes [38]. Unlike these studies, we investigate the relationship between the magnitude of the subjective burden and temporal evolution or motion of multiple joint angles and moments.

III. PARTIAL LEAST-SQUARES (PLS) REGRESSION FOR PRINCIPAL MOTION ANALYSIS (PMA)

In the PLS method, the covariance between multiple explanatory and objective variables that are continuous is analyzed to determine their relevant linear linkages [39]. In this work, the PLS is extended to the time-series data for one objective variable. Suppose that a motion is represented by n' types of time-series variables with a data length of l. In this case, a single sit-to-stand motion can be discretized into l moments. To express the motion at the k-th trial ($k = 1, \ldots, k'$) for participant s ($s = 1, \ldots, s'$), we establish vector $\boldsymbol{x}_k^{(s)}$ ($\in \mathbb{R}^{n'l \times 1}$) as follows:

$$\boldsymbol{x}_k^{(s)} = [\boldsymbol{x}_{1k}^{(s)\mathrm{T}}, \ldots, \boldsymbol{x}_{nk}^{(s)\mathrm{T}}, \ldots, \boldsymbol{x}_{n'k}^{(s)\mathrm{T}}]^{\mathrm{T}} \tag{1}$$

where, $\boldsymbol{x}_{nk}^{(s)}$ ($\in \mathbb{R}^{l\times 1}$) represents a column vector containing the time-series of the explanatory variable n ($n = 1, \ldots, n'$) for participant s at trial k. For example, $\boldsymbol{x}_{nk}^{(s)}$ can be a time-series of a certain joint angle or moment. Each s' participant undergoes k' trials. The motions of all the trials are represented as matrix $\boldsymbol{X}$ ($\in \mathbb{R}^{s'k'\times n'l}$):

$$\boldsymbol{X} = [\boldsymbol{x}_k^{(s)} : k = 1, \ldots, k', s = 1, \ldots, s']^{\mathrm{T}}. \tag{2}$$

The value of the objective variable at the k-th trial for participant s is expressed as $y_k^{(s)}$, and the values for all the trials and participants can be defined as

$$\boldsymbol{y} = [y_1^{(1)}, \ldots, y_k^{(s)}, \ldots, y_{k'}^{(s')}]^{\mathrm{T}}. \tag{3}$$

The model formulas for PLS are as follows:

$$\boldsymbol{X} = \sum_{i=1}^{a} \boldsymbol{t}_i \boldsymbol{p}_i^{\mathrm{T}} + \boldsymbol{E}_x \tag{4}$$

$$\boldsymbol{y} = \sum_{i=1}^{a} q_i \boldsymbol{t}_i + \boldsymbol{e}_y \tag{5}$$

where a is the number of principal motions adopted. $\boldsymbol{X}$ is decomposed into two matrices with column vectors $\boldsymbol{t}_i$ ($\in \mathbb{R}^{s'k'\times 1}$) and $\boldsymbol{p}_i$ ($\in \mathbb{R}^{n'l\times 1}$). $\boldsymbol{t}_i$ is the vector of the principal motion scores, which are the coordinates of the motion samples on the reduced space, and $\boldsymbol{p}_i$ is the vector of the principal motion loads. $\boldsymbol{y}$ is decomposed into a vectors, each of which is described by $q_i\boldsymbol{t}_i$, where q_i is a scalar value. $\boldsymbol{E}_x$ and $\boldsymbol{e}_y$ are the residuals for $\boldsymbol{X}$ and $\boldsymbol{y}$, respectively.

Based on these formulas, the scores and loads of the first principal motion can be computed. First, $\boldsymbol{t}_1$ is determined such that the covariance of $\boldsymbol{t}_1$ and $\boldsymbol{y}$ is maximized, as follows:

$$\boldsymbol{t}_1 = \frac{\boldsymbol{X}\boldsymbol{X}^{\mathrm{T}}\boldsymbol{y}}{\|\boldsymbol{X}^{\mathrm{T}}\boldsymbol{y}\|} \tag{6}$$

where $\| \bullet \|$ is the L2 norm. Next, $\boldsymbol{p}_1$ and q_1 are respectively calculated as

$$\boldsymbol{p}_1 = \frac{\boldsymbol{X}^T \boldsymbol{t}_1}{\|\boldsymbol{t}_1\|} \tag{7}$$

$$q_1 = \frac{\boldsymbol{y}^T \boldsymbol{t}_1}{\|\boldsymbol{t}_1\|} \tag{8}$$

such that the sums of the squared elements of $\boldsymbol{E}_x$ and $\boldsymbol{e}_y$ are minimized.

To compute the i-th ($i = 2, 3, \ldots$) principal motions, we define

$$\boldsymbol{X}_i = \boldsymbol{X}_{i-1} - \boldsymbol{t}_{i-1}\boldsymbol{p}_{i-1}^{\mathrm{T}} \tag{9}$$

$$\boldsymbol{y}_i = \boldsymbol{y}_{i-1} - q_{i-1}\boldsymbol{t}_{i-1} \tag{10}$$

where $\boldsymbol{X}_1 = \boldsymbol{X}$ and $\boldsymbol{y}_1 = \boldsymbol{y}$. $\boldsymbol{X}_i$ and $\boldsymbol{y}_i$ are the residuals after removing the parts expressed by up to the $(i-1)$-th principal motions from $\boldsymbol{X}$ and $\boldsymbol{y}$, respectively. Therefore, $\boldsymbol{t}_i$ is calculated as

$$\boldsymbol{t}_i = \frac{\boldsymbol{X_i}\boldsymbol{X_i}^{\mathrm{T}}\boldsymbol{y_i}}{\|\boldsymbol{X_i}^{\mathrm{T}}\boldsymbol{y_i}\|}. \tag{11}$$

Similar to the first principal motions, $\boldsymbol{p}_i$ and q_i are calculated using $\boldsymbol{t}_i$, $\boldsymbol{X}_i$, and $\boldsymbol{y}_i$. The principal motions are independent of one another and do not statistically interfere.

$$\boldsymbol{t}_j \perp \boldsymbol{t}_k \quad (j, k \in \{1, \ldots, a\}, j \neq k). \tag{12}$$

IV. METHODS: APPLICATION TO SUBJECTIVELY EASY SIT-TO-STAND MOTION

This section describes the experimental methods and data analyses performed to demonstrate the proposed PMA extended by the PLS, considering subjectively easy sit-to-stand motions.

A. PARTICIPANTS

Six healthy male university students (22.2 ± 0.8 years, 172.2 ± 4.4 cm, 59.6 ± 8.7 kg), who provided written informed consent, participated in this experiment. The participants were not informed of the study objectives. None of the participants reported a history of diseases that affected sit-to-stand movement.

B. APPARATUS

As shown in Fig. 1, a height-adjustable chair was used in this experiment, with the height adjusted to the knee level of each participant. A bilateral handrail was used, and the distance between the two handrails was 0.7 m. The handrails were adjusted to the height of the greater trochanter when the participants were standing. When sitting on the chair, the participants were instructed to match the middle of their thigh and fore edge of the chair and maintain the distance between the two feet as the distance between their acromia. These configurations are summarized in Table 1. To control the posture of the head, a mark was introduced at a height of 1.7 m, 3 m in front of the chair. The participants were instructed to look at the mark throughout the sit-to-stand movement.

TABLE 1. Configurations of sit-to-stand task and initial trunk tilt angle and positions of the hands and feet.

Hand rail height	Great trochanter at the stand-up posture					
Hand rail width	0.7 m					
Feet width	Distance of acromia					
Sampling rate	100 Hz					
Trunk angle	3 levels	15°	30°	45°		
Grip position	5 levels	H_1	H_2	H_3	H_4	H_5
Ankle position	3 levels	A_1	A_2	A_3		

The forces applied to the handrails were measured using force sensors (six-axial, PFS055YA251, Leptrino, Japan) installed inside the handrails. One force sensor was installed on each of the two poles supporting a handrail. The ground reaction force applied to each foot was measured using a force plate (M3D-FP-A, Tec Gihan Co. Ltd., Japan). A motion capture system (MAC 3D system, Motion Analysis Corporation, U.S.) was used to obtain the posture of the body to determine the angles of the upper-limb and lower-limb joints. Markers were set at the scapulae, elbow joints, wrist joints, greater

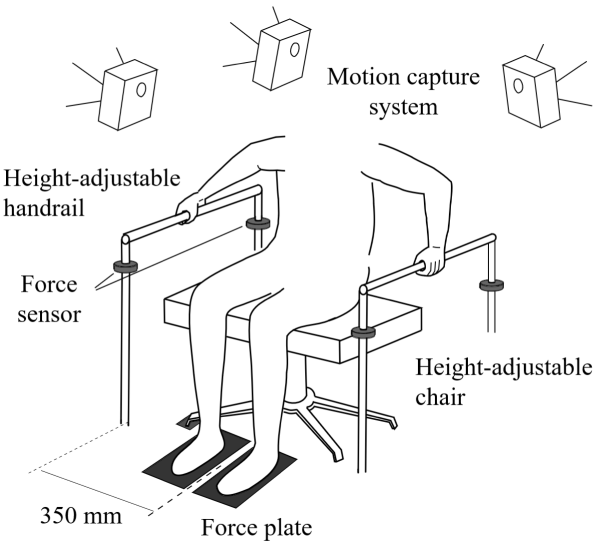

FIGURE 1. Apparatus and experimental setup. The joint angles were monitored using a motion capture system. The ground reaction forces and handrail forces were measured.

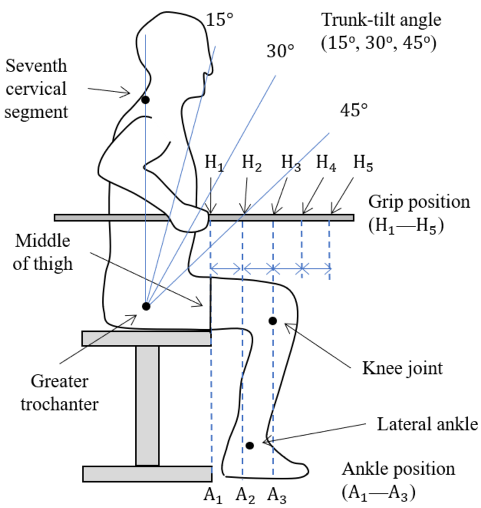

FIGURE 2. Position of the feet, grip on the handrails, and tilt angles. The three parameters were varied in the standing-up trials.

trochanters, knee joints (lateral femoral condyle), ankle joints (lateral malleolus), calcanei, distal phalanx of each foot, and the seventh cervical segment. All the data were sampled at 100 Hz.

C. TASKS

The participants repeatedly stood up from a seated position on the chair. For each trial, we varied or controlled the initial posture. The parameters to control the posture included the trunk-tilt angle, grip position, and foot (ankle) position. Three to five levels for each parameter were considered as listed in Table 1. As shown in Fig. 2, three initial trunk-tilt angles (15°, 30°, 45°) were considered as the angle between the trunk vector and gravity vector. The trunk vector was defined by the center of the greater trochanters and seventh cervical segment. The participants were instructed not to flex their trunk before they rose from the seat. In other words, the participants did not leverage the angular momentum of the trunk to stand up. Further, five grip positions (H_1, H_2, H_3, H_4, H_5) and three ankle positions (A_1, A_2, A_3) were considered. Positions H_1 and A_1 matched the middle of the thigh, whereas H_3 and A_3 matched the knee joint. H_2 and A_2 were positioned at the center of H_1 and H_3 and A_1 and A_3, respectively. The distances for H_3–H_4 and H_4–H_5 were the same as that between H_1 and H_2. The participants started their stand-up motion with the initial conditions defined by the three parameters. At the standing-up position, the participants' trunks were upright while gripping the handrail. The participants pushed the handrails downward, without any pulling motion. The participants did not change the position of the grip or feet during a single standing-up motion. Further, during the motions, the complete soles were in contact with the ground. We determined the parameters through informal experiments in which the subjectively easiest motions were likely to be included in the space established by these parameters. For example, when the trunk-tilt angle is smaller than 15°, it is relatively difficult or tiring to stand up; hence, we excluded such small trunk-tilt angles. Similarly, when the ankle is positioned in front of A_3 or the grip is positioned behind H_1, the standing-up motion involves a large subjective burden, and thus, such parameters were excluded.

By varying the three types of parameters, 33 conditions were implemented in a randomized order in a single set. These 33 conditions did not exhaustively include all the combinations of the three parameters because certain combinations resulted in virtually impossible motions. Under these difficult conditions, only a few or none of the participants could perform the standing-up motions. For example, none of the participants could stand up when the initial trunk angle was 15° and the grip and ankle positions were H_1 and A_3, respectively. Each participant performed two experimental sets, and a total of 66 motions were recorded.

The level of subjective burden was investigated through the magnitude estimation method. First, the participants were instructed to practice the sit-to-stand movement under the reference condition, wherein the trunk-tilt angle, grip position, and ankle position were 30°, H_3, and A_2, respectively. The experienced subjective burden for the complete body in this condition corresponded to a score of 100. Among the tested conditions, the reference condition incurred a moderate burden. After each trial of the sit-to-stand movement, the participants assigned a certain score to the subjective burden. A higher score represented a heavier load. If a participant felt a certain motion was two times more tiring than the reference motion, the score was 200. The movement speed and force applied to the handrails were determined by the participants themselves such that they could perform the standing-up motions naturally. The participants were instructed to avoid the generation of laterally asymmetric motions as much as possible.

D. DATA ANALYSIS

1) COMPUTATION OF JOINT ANGLES AND MOMENTS

The ankle angle was the angle between the calf and gravity vector. The knee angle represented the flexion of the knee joint. The trunk-tilt angle was defined as the angle between the gravity vector and trunk vector connecting the seventh cervical segment and center of the greater trochanters. The shoulder angle was computed as the inner product of the trunk vector and upper-arm vector, whereas the elbow angle was the flexion of the elbow joint. These angles were zero at the upright standing position. The internal static joint moments were computed and used for further analysis because the acceleration of the motion was small. Directions to support the body weight were defined positive. The mean values of the bilateral limbs were used to compute the angles and moments of the joints assuming laterally symmetric motions.

2) CYCLE OF SIT-TO-STAND MOTION AND NORMALIZATION

The period from the seating-off to the instant at which the angular velocity of the trunk became zero was normalized to a 100% cycle. The joint moments were normalized according to the height and weight of each participant. The scores of the subjective burden assigned by the participants were normalized by the geometric mean of the scores of all the trials.

3) PMA EXTENDED WITH PLS

In this study, the magnitude of the subjective burden was the objective variable, whereas the time-series of the ankle, knee, trunk, shoulder, and elbow joint angles, as well as the ankle, knee, hip, shoulder, and elbow joint moments, were considered as the explanatory variables ($n' = 10$). The time-series were discretized into 101 instants: $l = 101$. For each instant, the explanatory variables, i.e., joint angles and moments, were normalized as the z-scores for the individuals. Because each of the six participants conducted 66 trials, $k' = 66$ and $s' = 6$.

V. RESULTS

A. CORRELATION BETWEEN THE PRINCIPAL MOTIONS AND SUBJECTIVE BURDEN

Table 2 lists the correlation coefficients between the scores of the four major principal motions and magnitude of the subjective burden. Based on the correlation coefficients, the first three principal motions were considered in this work. The linear combination of these three principal motions exhibited a correlation coefficient of 0.74 with the reported subjective burdens. Even when the fourth principal motion was included, the correlation coefficient exhibited only a slight increase, reaching 0.77. Bartlett's test can be used to determine the number of principal components for PCA. This test was incorporated in the present analysis; however, this approach resulted in a larger number of significant principal motions, i.e., nine, several of which exhibited extremely small correlation coefficients with the subjective burdens. Hence, we did not adopt Bartlett's test as a criterion to determine the number of principal motions.

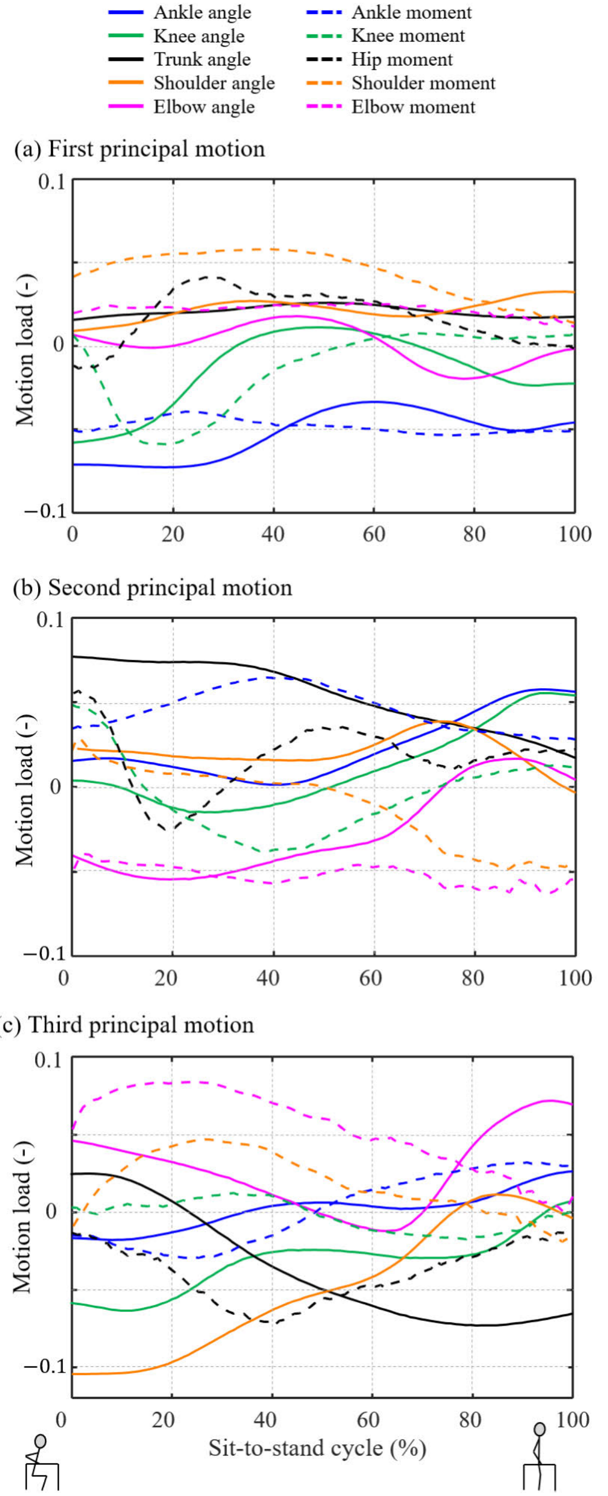

FIGURE 3. Loads of the three principal motions. Zero of the vertical axis represents the mean value of all the trials. A positive load indicates that the corresponding joint angle or moment is greater than that of the mean sit-to-stand motion.

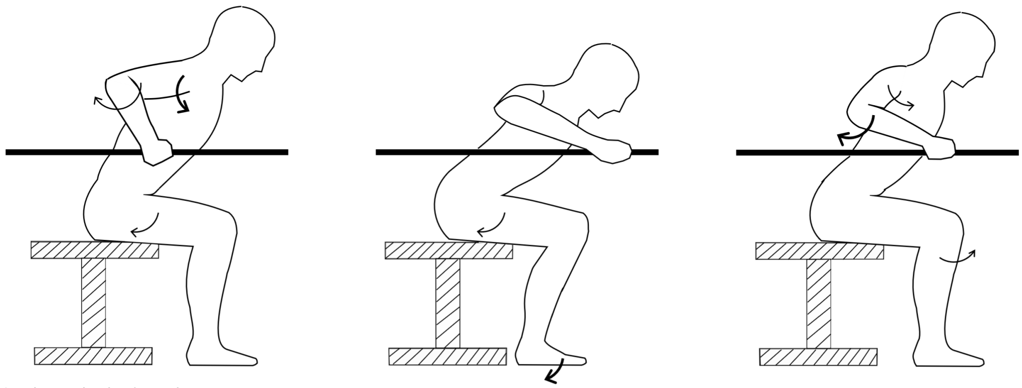

FIGURE 4. Schematic of the initial positions and moments represented by the individual principal motions. The arc arrows are the representative internal joint moments. (a)–(c) correspond to the first–third principal motions.

TABLE 2. Correlation coefficients between the scores of each principal motion and magnitude of the subjective burden.

Principal motion	Correlation coefficients
First	0.60
Second	0.27
Third	0.19
Fourth	0.14

B. PRINCIPAL MOTIONS

This section describes each principal motion and its meaning based on the corresponding loads of the joint angles and moments ($\boldsymbol{p}_i$). Fig. 3 shows the loads for each principal motion. The zero of the vertical axis represents the mean value of all the trials at each motion cycle because all the variables were normalized to z-scores before being applied to the PMA-PLS, as described in Section IV-D3. Hence, at a certain motion cycle, a positive load of a joint angle or moment indicates that the angle or moment is greater than the mean joint angle or moment at the corresponding motion cycle. In Section VI, these principal motions are discussed based on the relationships between the center of the body mass and base of the support.

1) FIRST PRINCIPAL MOTION

The load of the first principal motion is shown in Fig. 3 (a). At 0% of the cycle, the ankle and knee angles are substantially smaller than the average, i.e., zero, indicating that the feet are in the anterior positions when seating-off. The moment of the knee joint is small in the first half of the motion. Subsequently, the moment returns to the normal level at approximately 50% of the cycle. The moment of the hip joint exhibits an opposite trend to that of the knee. Specifically, the moment of the hip joint is relatively larger than the average in the first half cycle and gradually returns to the average level. The moment of the ankle joint is considerably smaller than the average throughout the cycle, whereas the shoulder and elbow joint moments are larger than the average. Relatively large moments are applied to the upper limbs.

Collectively, the sit-to-stand movement represented by the first principal motion is performed as follows. The feet are placed in the anterior positions, and later, the hip and arms are leveraged to raise the body. In other words, the knee and ankle joints are not efficiently used to stand up. A typical initial posture represented by the first principal motion is shown in Fig. 4 (a). Note that the movements that are dominant in the first principal motion incur a large subjective burden.

2) SECOND PRINCIPAL MOTION

As shown in Fig. 3 (b), in this motion, the initial trunk-tilt angle and angle of the elbow joint is considerably larger and smaller than the average, respectively. In other words, the grip position pertains to relatively anterior positions. In the last phase of the cycle, the angles of the ankle and knee joints are larger than the average, which indicates that the knees are not entirely extended. This phenomenon occurs when the participants place their hands in anterior positions. In terms of the moments, the moment of the ankle joint is relatively large throughout the cycle. The moment of the knee joint is smaller than the average at the central part (∼40%).

In this motion, the initial upper trunk is relatively flexed, and the grip position is relatively anterior. The participants do not or cannot utilize their arms to support their body weights because the grip position is far from the center of the body owing to the relatively extended elbows. Instead, the weight of the body, which is leaned forward, is mainly balanced by the ankle moments. A typical initial position represented by the second principal motion is shown in Fig. 4 (b).

3) THIRD PRINCIPAL MOTION

As shown in Fig. 3 (c), initially, the angles of the knee joints are smaller than the average, indicating that the feet are positioned anteriorly. The initial trunk-tilt angle is larger than the average and decreases sharply, indicating that the extension of

TABLE 3. Criteria to judge the valid synthesized motions.

Index	Value
Ankle angle at 0% of the cycle	$< 30°$
Knee angle at 0% of the cycle	$< 110°$
Trunk angle at 0% of the cycle	$< 50°$
Ankle angle at 100% of the cycle	$< 10°$
Knee angle at 100% of the cycle	$< 10°$
Trunk angle at 100% of the cycle	$< 5°$
Moment of the elbow and shoulder joints through the entire cycle	≥ 0

the upper trunk is relatively rapid. The angles of the shoulder and elbow joints indicate that the grip position is close to the knee. In this motion, the hip joint bears less burden in the central phase. Large shoulder and elbow moments indicate that a large force is applied to the handrail in the first half phase, thereby assisting the extension of the upper body. A typical initial position represented by the third principal motion is shown in Fig. 4 (c).

VI. SYNTHESIS OF THE SIT-TO-STAND MOTION WITH A SMALL SUBJECTIVE BURDEN

A. METHOD TO SYNTHESIZE SUBJECTIVELY EASY SIT-TO-STAND MOTIONS

Based on the relationships between the principal motions and subjective burdens, to determine the sit-to-stand motions with small subjective burdens, we investigated a number of combinations of the three principal motions. Fig. 5 shows the distribution of the motion trials in the space of the principal motion scores. As each score was positively correlated with the subjective burden, the scores in the bottom left regions were considered to correspond to less tiring motions. We exhaustively synthesized the motions in the regions covered by the scores of -30 to 0 for each principal motion, covering 2700 (30^3) motions.

The sit-to-stand movements in this region comprised impossible or unrealistic motions. Furthermore, certain motions did not end in a complete standing-up posture. To ensure that the synthesized motions were complete and realistic, a series of evaluation criteria, as listed in Table 3, were adopted. The synthesized motions that did not satisfy the conditions in the table were judged invalid. At the beginning of a sit-to-stand motion (0% motion cycle), we set the maximal ankle angle as 30°, knee angle as 110°, and trunk angle as 50°. The initial postures with trunk-tilt angles greater than 50° were regarded unnatural. Moreover, the postures with ankle angles greater than 30° are difficult to accomplish, for most individuals, while ensuring that the complete sole is in contact with the ground. Furthermore, these three joint angles were required to be sufficiently small at the end of the motion to complete the standing-up motion. We regarded the postures with the trunk-tilt, knee, and ankle angles smaller than 5°, 10°, and 10°, respectively, at 100% of the motion cycle as complete standing-up postures. Moreover, the moments of the elbow and shoulder joints could not be negative.

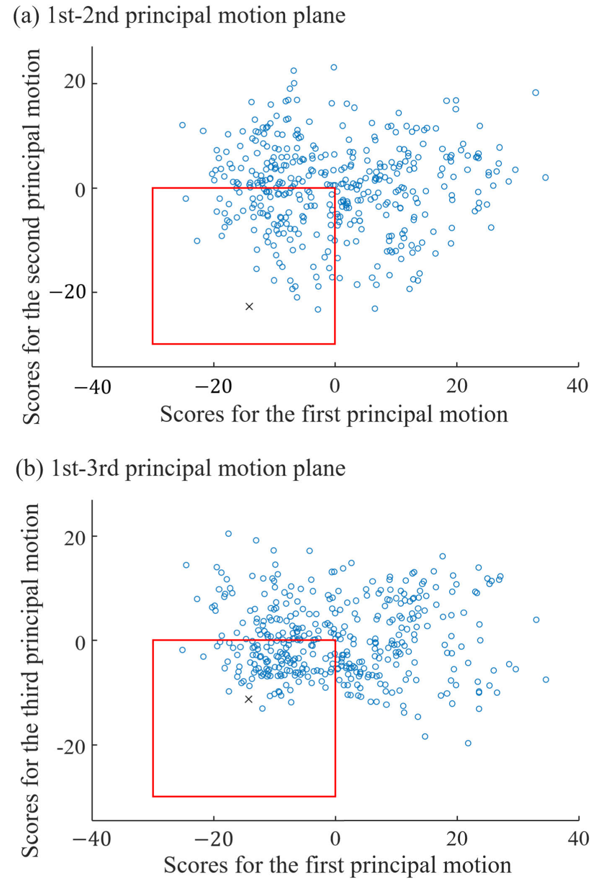

FIGURE 5. (a) Distribution of the sit-to-stand motions based on the first and second principal motion scores. (b) Distribution based on the first and third principal motion scores. Blue circles indicate the observed motion samples, and the red box is the area in which easy sit-to-stand conditions were identified. The cross represents the synthesized motion whose subjective burden is predicted to be the smallest.

B. SYNTHESIZED SUBJECTIVELY EASY MOTION

The synthesized motion with the smallest subjective burden appears at the coordinates (-14, -23, -11), represented by a cross in Fig. 5, in the three-dimensional principal motion space. In addition, the second and third easiest conditions also occur near this coordinate, as indicated in Table 4. Owing to the similarity in the three conditions, only the easiest condition is described herein. Assuming the weight and height of the participant as 60 kg and 172 cm, respectively, the simulated angles and moments of joints are shown in Fig. 6.

TABLE 4. Principal motion scores for the three easiest motions synthesized by the three major principal motions.

Rank	First principal motion	Second principal motion	Third principal motion
1	-14	-23	-11
2	-15	-23	-9
3	-12	-23	-14

The initial tilt angle is nearly 20°, and the feet are placed at a relatively posterior position because the initial knee angle is approximately 100°. The corresponding initial posture is

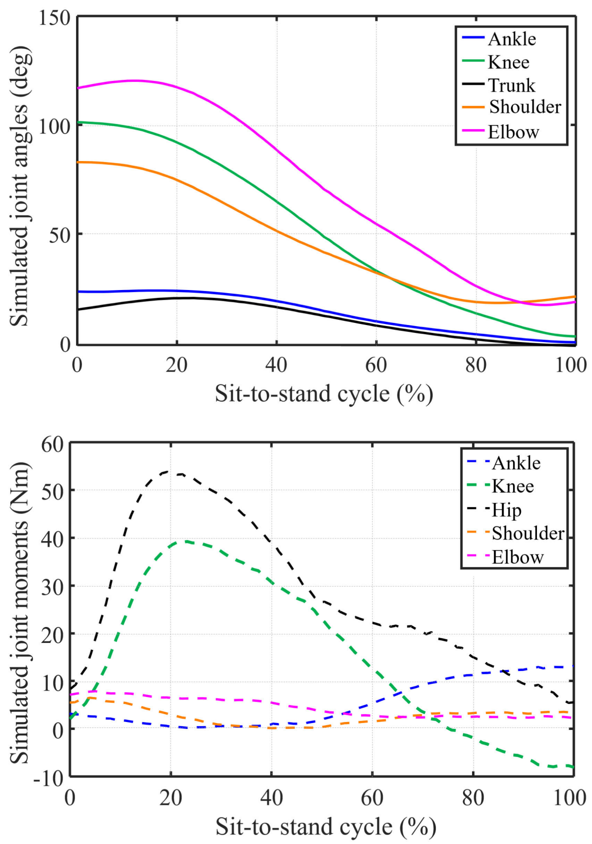

FIGURE 6. **Synthesis of the condition that results in the minimum subjective burden. (a) and (b) pertain to the joint angles and moments, respectively.**

shown in Fig. 7. Considering the angles of shoulder and elbow joints when seating off, the grip position is above the point close to the middle part of the thigh. The angles of the ankle joint, knee joint, and trunk are nearly zero at 100% of the cycle, in accordance with the standing posture.

Handrails are not intensively used to support the body weight because the shoulder and elbow moments are relatively small. The knee and hip moments are maximized at approximately 20% of the cycle and then gradually decrease. In contrast, the ankle moment does not clearly exhibit a local peak and starts to increase after 50% of the cycle. These characteristics of moments are consistent with those for the natural or unrestricted sit-to-stand motions without handrails [22], [37], [40], [41]. After approximately 80% of the cycle, a negative knee moment occurs, indicating that the gravity of the upper body generates a reverse moment on the knee joint, which has also been observed for the motions without handrails [22], [35], [37], [41].

C. EXPERIMENTAL VALIDATION OF SYNTHESIZED MOTION

1) PARTICIPANTS AND TASKS

We invited 15 participants (male students, age: 22.7 ± 1.0 years, height: 173.5 ± 4.6 cm, weight: 61.5 ± 8.9 kg) including the six participants in the experiment described in Section III to a simplified experiment to evaluate the synthesized motion. The participants provided written informed consent.

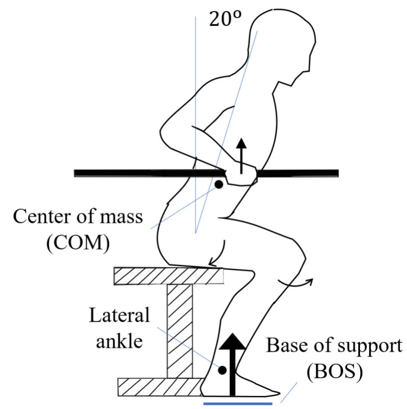

FIGURE 7. **Initial conditions of the subjectively easy sit-to-stand movement synthesized by the three principal motions.**

Three types of initial postures were ranked. Posture 1 corresponded to the initial posture of the synthesized subjectively easiest motion: (trunk-tilt, grip position, ankle position) $= (20^o, H_1, A_1)$, as shown in Fig. 7. Posture 2 corresponded to the conditions used as a reference in the experiment described in Section III: (trunk-tilt, grip position, ankle position) $= (30^o, H_3, A_2)$. Posture 3 corresponded to a relatively difficult condition: (trunk-tilt, grip position, ankle position) $= (15^o, H_3, A_2)$. Each initial posture was evaluated only once by the individual participants. The initial postures and motions were monitored by experimenters and videotaped for post-review. The ground reaction forces and handrail forces were not recorded. As in the task described in Section IV, the participants did not move their feet and grip positions from the designated initial positions during the sit-to-stand motion. Subsequently, the participants ranked the three postures that were experienced in randomized order. The participants were instructed to perform the ranking based on the burden experienced by the complete body. One rank could only be assigned to a one posture.

2) RESULTS

Nine among the 15 participants selected posture 1 as the easiest, and the remaining six participants selected posture 2. Thirteen and two among the 15 participants felt that postures 3 and 2, respectively, were the most difficult conditions to stand up. Wilcoxon signed-rank tests with the Bonferroni correction were applied to the assigned ranks. We observed a significant difference between postures 1 and 3 ($V = 120$, $z = 3.41, p = 6.10 \times 10^{-4} < 0.001/3$) and between postures 2 and 3 ($V = 110$, $z = 2.84$, $p = 0.00280 < 0.01/3$), and no difference between postures 1 and 2 ($V = 78$, $z = 1.02$, $p = 0.297 > 0.05/3$). Posture 1, which was the initial posture of the supposedly easiest motion, was judged to be easier than posture 3; however, a clear difference between postures 1 and 2 was not observed in terms of the subjective burden.

VII. DISCUSSION

In this section, we discuss and interpret the cause of the subjective difficulty for each principal motion in terms of the center of mass (COM) and base of support (BOS), because, in general, sit-to-stand motions are considered to be a transfer of the COM to the region above the BOS or the center of ground reaction force [27], [42].

The initial posture represented by the first principal motion is shown in Fig. 4 (a). The feature of this posture is that the feet are in an anterior position. Under this condition, at the instant of seating off, the position of the COM was considerably behind the BOS. The COM was required to be moved forward while lifting up to complete the sit-to-stand motion. To this end, the participants were required to strongly push the handrails to move their body upward, which resulted in large shoulder moments, as shown in Fig. 3 (a). In general, the initial knee angle should be large, and the foot position should not be far from the COM [24], [25]. The motions represented by the first principal motion is inefficient. Moreover, the COM was shifted forward, above the BOS, by the hip and elbow extension moments. In previous reports [25], [43], the hip moments were also comparatively large when the feet were anterior. To compensate for the initial gap between the COM and BOS, additional shoulder, elbow, and hip torques were required, which likely led to a large subjective burden.

The initial posture represented by the second principal motion is shown in Fig 4 (b). The key features of this motion were the large trunk-tilt angle and ankle moments throughout the motion. Without the handrail use, an excessively large initial trunk-tilt angle results in a longer period of large supportive joint moments and a less effective sit-to-stand motion [26]. With the handrail use in the present study, to lift up the overly tilted upper body, relatively large shoulder, elbow, and hip moments were required during the initial 0–10% phase. Subsequently, to cancel the moment of the body to lean forward, large ankle torques were required to be implemented until the end of the motion because the COM was located in the anterior position due to the large trunk-tilt angle. Furthermore, relatively large hip moments were required, except in the 10–30% phase, because the COM was far from the hip and the moment arm about the hip was large. Moreover, the initial height of the COM was small, and greater energy was required to transfer the COM to correspond to the upright position.

The initial posture represented by the third principal motion is shown in Fig. 4 (c). The main differences between this motion and the second principal motion pertain to the position of the handrail grip and trunk-tilt angle. In the representative third principal motion, the foot position was anterior, and the COM did not lay on the BOS. As mentioned previously, owing to the initial gap between the COM and BOS, the use of handrails was required to accomplish the sit-to-stand motion because such gap between the COM and BOS leads to low stability during the motion [44]. This principal motion relied considerably on the handrails, i.e., the elbow and shoulder moments.

In contrast, as shown in Figs. 6 (a) and 7, in the case of the synthesized supposedly easy sit-to-stand motion at the initial knee angle of approximately 100^{o}, the feet positions were posterior. In fact, this knee angle was similar to that of natural sit-to-stand motion [41]. In general, posterior feet positions lead to effortless sit-to-stand motions [45]–[47]. Further, the COM, BOS, and grip position were aligned nearly vertically. In this configuration, the horizontal transfer of the COMs was eliminated under the settings of the present study, in which the participants did not utilize the momentum caused by tilting the upper body. Furthermore, this alignment benefited the participants as the reaction force from the handrail did not produce moments to lean forward or backward about the COM. These aspects likely explain the reasonably low burden in synthesized motion or initial condition.

As shown in Fig. 6 (b), the moments of the upper limbs were small, with a maximum value of only 10 Nm. The moment values of the lower limbs were similar to those observed when healthy people stand up without handrails, as reported in [22], [41]. Thus, in our experimental settings, the healthy young participants likely did not substantially depend on the handrails. In general, in the case of healthy young people, the decrease in the lower-limb moments is only approximately 10% because of the use of handrails, potentially because such individuals do not rely on the handrails [16]. This result is consistent with that reported in a study in which healthy people used handrails to ensure postural stability rather than to decrease the required moments of the lower-limb joints [48].

As described in Section V, the synthesized motion (posture 1) and posture 2 could not be clearly discerned in terms of the subjective burdens. This phenomenon likely occurred owing to the small difference in the subjective burden between postures 1 and 2 for young university students. In the experiment described in Section V, the participants' stand up motions were not controlled, whereas their initial positions were controlled. Thus, the participants could select the most effortless motion, irrespective of the initial postures.

This study has certain limitations. First, the motions synthesized by the principal motions may not necessarily be executable. Because we adopted certain criteria, as described in Table 3, the motions pertaining to the linear combinations of the three principal motion appeared to be executable in this study; however, general methods to evaluate whether the synthesized motions are biomechanically possible must be established. Second, the forward trunk-tilting motion was controlled in our experiment, although the angular momentum of the upper body is transferred to the lower limbs in effective and natural sit-to-stand motions [27], [40], [42], [49]. Hence, our investigation likely did not target natural motions. Nonetheless, the considered situation is expected to be close to the sit-to-stand motion assisted by a supportive machine [50], [51], in which the user does not perform fast trunk-tilting motion. Furthermore, our experiment was designed to investigate the feasibility of the PMA to evaluate subjectively easy sit-to-stand motion involving healthy participants. Hence, the experimental condition was simplified and only a few of many determinants of sit-to-stand motions [7] were considered. A truly subjectively easy motion may be achieved by considering a number of these determinants collectively. Such motions should be investigated for disabled people in future. Finally, the principal motions found in the present study involved only six healthy young participants. Although the principal motions are semantically valid, they might have been biased by the small group of participants.

VIII. CONCLUSION

A combination of PMA and PLS was adopted to analyze and synthesize human motions, enabling the determination of the principal motions that are independent of one another, correlated with a continuous objective variable. To validate the performance of the proposed approach, subjectively easy sit-to-stand motions with handrail use were examined. Based on the various motions performed by six healthy young people, we computed the principal motions of sit-to-stand motions correlated with the magnitude of the subjective difficulty experienced throughout the motion. Three independent principal motions, whose meanings could be reasonably interpreted, were considered to synthesize the subjectively easy motion. Finally, reasonably subjectively easy motions or initial postures were determined; however, the young participants could not significantly discern the synthesized and reference motions in terms of the subjective easiness. The proposed method can be used to investigate the principal motions of redundant time-series systems with continuous objective variable to supervise the motions. Potential applications comprise the combination with online motion recognition techniques using wearable sensors [52] or cameras [53] to navigate people to motions with less burdens.

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