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The kinetic mechanisms of vertical pointing movements

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ABSTRACT

The present study utilized induced acceleration analysis to clarify the contributions of muscular and gravitational torques to the kinematics of vertical pointing movements performed by the upper limb. The study included eight healthy men with a mean age of 25 years. The experiment was divided into three blocks with ten trials in each, comprising five upward and five downward, randomly executed movements. The movements were recorded by a motion capture system and were subsequently analyzed. During the deceleration phase of the upward movement and the acceleration phase of the downward movement, the angular acceleration induced by gravitational torque contributed more to the generation of net induced angular acceleration than the angular acceleration induced by muscular torque. In addition, the difference between the net induced angular acceleration profiles during the upward and downward movements was mainly attributable to the difference between the respective angular acceleration profiles induced by muscular torque. These findings suggest that the central nervous system considers the gravitational effect on the upper limb in a phase-specific manner and accordingly generates a torque-derived kinematic difference with respect to the movement direction.

1. Introduction

In the course of daily life, humans are able to execute various movements while being exposed to gravity, which pulls the body downward. Because the gravitational force always acts downward, its functional effect on movement depends on the direction of movement. For example, gravity decelerates upward movement but accelerates downward movement. Despite the gravitational constraint, humans are able to achieve the purpose of the movements by integrating gravitational information into the central process of generating movement [1, 2, 3, 4, 5, 6, 7].

Most of the previous studies on this subject have focused on gravitational integration into the central processes of the vertical (upward and downward) movements of the upper limbs. A vertical movement that is directionally dependent on the effect of gravity on the body can be experimentally investigated to establish how the central nervous system (CNS) processes gravity for movement generation.

Previous studies have found that the kinematics for upward movement differs from that for downward movement (e.g., acceleration duration is shorter for upward than downward movements) in a normal gravitational environment (1G) [1, 2, 3, 4, 6, 7, 8], while the direction-dependent differences are attenuated in a microgravitational environment [9, 10]. It has been suggested that the direction-dependent differences of kinematics in 1G conditions represent utilization of the gravitational effect on the body [4, 11]. Several studies have also demonstrated the control policy for vertical pointing movements through numerical simulated and experimental approaches [3, 9]. In this study, we introduce an induced acceleration analysis (IAA), which is a forward dynamic approach [12, 13] for the purposes of elucidating how the CNS controls a vertical pointing movement considering the effect of gravity on the body. This method enables examination of how muscular and gravitational torques contribute to the kinematics of movement, i.e., the relationship between kinetics and kinematics during the movement. Although previous studies have revealed the control policy from the perspective of optimal control [3, 9], how the kinetic parameters (i.e., torques) resulted in the kinematics of vertical movement was not explicitly indicated. The IAA has been used for the analyses of human movements such as throwing [12] and quiet standing [13], but not for the analysis of vertical pointing movement by the upper limb. Therefore, the application of the IAA to the analysis for the vertical pointing movement can elucidate more clearly the mechanisms of the movement from the point of the relationship between kinetics and kinematics. The

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present study contributes to the current understanding of the motor control mechanism underlying vertical pointing movement from the perspective of forward dynamic analysis.

2. Materials and methods

2.1. Participants

Eight healthy adult men with a mean age of 25 (range 22–29) years were enrolled in the present study. All participants were confirmed to be right-handed according to the Edinburgh Handedness Inventory [14]. Before the experiments, the experimental procedure was explained to all participants, who gave their written informed consent. The study was approved by the Ethics Committee of the Osaka University of Health and Sport Sciences and conducted in accordance with the Declaration of Helsinki.

2.2. Materials and procedure

Each participant was required to sit on a chair in front of three spherical target objects (1.1 cm in diameter), with his head and trunk aligned with the vertical axis of the earth. The target objects were made from styrene foam and attached to a pole which was placed vertically in a row, with the middle object in line with the right shoulder of the participant. The upper and lower objects were positioned at an angle of 15° upward and 15° downward, respectively, relative to a line between the right shoulder and the middle object. Although the gravitational effect depends on the posture of the upper limb, an angle of 15° induces kinematic asymmetry between upward and downward movements [15]. The participant was asked to execute single-joint upward and downward pointing movements using the right upper limb (i.e., by rotation of the shoulder joint in the sagittal plane). The participant was allowed to do this at a comfortable velocity. Splints were used to immobilize the elbow and wrist joints of the participant to ensure the execution of a single-joint movement. The experiment was divided into three blocks, with each block consisting of ten trials. The ten trials consisted of five upward and five downward movements, which were randomly executed. Rest periods of approximately 30 seconds between trials and 2 minutes between blocks of the experiment were allowed to prevent muscle fatigue. Prior to the commencement of the actual experiment, the participant was allowed ten practice trials of the upward and downward movements.

At the beginning of each movement trial, an initial beep signal was used to instruct the participant to align his right upper limb with the middle target (the initial target). Five seconds later, one of two types of beep signal was used to instruct the participant to fixate on one of the other two targets. A single short beep was an instruction to fixate on the upper target in preparation to move the limb toward it at the next signal, while two short beeps was an instruction to fixate on the lower target in order to move the limb toward it at the next signal. The signal for the participant to execute the indicated movement comprised a single short beep and was given two seconds later.

Movements were recorded using a motion capture system (OptiTrack, NaturalPoint, Inc., Corvallis, OR, USA) at a sampling frequency of 100 Hz. Infrared reflective markers (8 mm in diameter) were placed on the right shoulder, wrist, and index fingernail of the participant.

2.3. Data analysis

The position data obtained through the markers were filtered using a fifth-order Butterworth low-pass filter with a cut-off frequency of 5 Hz. The data were analyzed in two-dimensional space, wherein the vertical and antero-posterior axes constituted the sagittal plane. Two axes were used because the experimental motor tasks consisted of vertical pointing movements by rotation of the shoulder joint in the sagittal plane. We analyzed the peak deviation angle of the upper limb in the horizontal plane during the movement, and confirmed that the vertical movement was precisely performed by all participants (mean ± standard error for the upward movement, 0.52° ± 0.06°; for the downward movement, 0.82° ± 0.04°).

The angular velocity and acceleration of the upper limb were calculated from the angular displacement of the upper limb relative to the vertical using a three-point differential algorithm. The initiation and termination of each trial movement were defined by the first and last points at which the angular velocity exceeded 0.01 rad/s, respectively.

Before commencing IAA, we first carried out an analysis of the following kinematic parameters: movement duration (MD; the time between movement initiation and termination), acceleration duration (AD; the time between movement initiation and the attainment of peak angular velocity), deceleration duration (DD; the time between peak angular velocity and movement termination), absolute peak angular acceleration (PA), duration to peak angular acceleration (DPA; the time between movement initiation and the attainment of peak angular acceleration), absolute peak angular deceleration (PD), and duration to peak angular deceleration (DPD; the time between movement initiation and the attainment of peak angular deceleration).

Inverse dynamic analysis of the measured kinematic data was used to compute the following torque parameters: muscular torque (MT), gravitational torque (GT), and net torque (NT; the sum of MT and GT) around the shoulder. The anthropometric data presented by Winter [16] were used for this purpose. The equations for MT and GT are as follows (Eqs. (1) and (2)):

$$\boldsymbol{MT} = \mathrm{Im} \cdot \ddot{\boldsymbol{\theta}} m + \boldsymbol{L} \times (m\boldsymbol{a} - m\boldsymbol{g}) \tag{1}$$

$$\boldsymbol{GT} = \boldsymbol{L} \times m\boldsymbol{g} \tag{2}$$

where Im, $\ddot{\theta}$m, L, m, a, and g denote the moment of inertia, measured angular acceleration vector, directional vector between the shoulder and the center of mass of the arm, mass of the arm, translational acceleration vector of the center of mass of the arm, and acceleration due to gravity (9.81 $\mathrm{m/s^2}$), respectively. The moment of inertia Im is given by Eqs. (3) and (4):

$$Im = mk^2 \tag{3}$$

$$k = Kl \tag{4}$$

where k, K, and l are the radius of gyration, ratio of the radius of gyration, and length of the arm, respectively.

Using the obtained torque data, we calculated the induced angular accelerations by IAA and were able to determine how MT and GT induced the kinematics of vertical pointing movement (e.g., angular accelerations). Although IAA can also be used to determine the angular acceleration induced by a velocity-dependent torque, such torque and angular acceleration were not applicable in the present study owing to the consideration of single-joint rotation. The angular accelerations induced by MT and/or GT were calculated using Eqs. (5), (6), and (7):

$$\ddot{\boldsymbol{\theta}}\boldsymbol{net} = \boldsymbol{I}(\boldsymbol{\theta})^{-\mathbf{1}}(\boldsymbol{MT} + \boldsymbol{GT}) \tag{5}$$

$$\ddot{\boldsymbol{\theta}}\boldsymbol{mt} = \boldsymbol{I}(\boldsymbol{\theta})^{-\mathbf{1}} \cdot \boldsymbol{MT} \tag{6}$$

$$\ddot{\boldsymbol{\theta}}\boldsymbol{gt} = \boldsymbol{I}(\boldsymbol{\theta})^{-\mathbf{1}} \cdot \boldsymbol{GT} \tag{7}$$

where $\ddot{\theta}$net, $\ddot{\theta}$mt, $\ddot{\theta}$gt, and I(θ) denote the net angular acceleration vector induced by MT and GT, angular acceleration vector induced by MT, angular acceleration vector induced by GT, and inertia term vector, respectively. The inertia term vector is given by Eq. (8):

$$\boldsymbol{I}(\boldsymbol{\theta})^{-1} = Im + m\boldsymbol{L}^2 \tag{8}$$

To enable detailed evaluation of the induced angular accelerations, we also calculated the following parameters: net induced acceleration duration (IADnet; the time between movement initiation and the attainment of the peak net induced angular velocity), net induced deceleration duration (IDDnet; the time between the attainment of peak net induced angular velocity and movement termination), absolute peak net induced angular acceleration (PIAnet), duration to peak net induced angular acceleration (DPIAnet; the time between movement initiation and the attainment of peak net induced angular acceleration), absolute peak net induced angular deceleration (PIDnet), and duration to peak net induced angular deceleration (DPIDnet; the time between movement initiation and the attainment of peak net induced angular deceleration).

Kolmogorov-Smirnov tests were used to evaluate the normality of the distributions of the measured and simulated (induced) parameters. When normal distributions were observed, we computed the mean values and performed a paired *t*-test to compare upward and downward movements. Conversely, when the parameters were not normally distributed, we computed the median values and used a Wilcoxon test for the comparison. A significance level of 0.05 was used for all comparisons.

3. Results

All eight study participants completed the experimental motor task and the data for the total of 240 trials were successfully acquired and analyzed. Based on the measured acceleration data, we computed the MT, GT, and NT values for the upward and downward movements (see Figure 1(a) and (b)). The MT profiles for the upward and downward movements (dotted lines) were similar to the NT profiles, with the exception of the offsets. Moreover, the MT and NT profiles for the upward movement appeared to be inversions of those for the downward movement. The negative values of the GT profiles for the upward and downward movements gradually decreased during the movements.

Using the obtained torque data, we performed IAA. The profiles of the induced angular accelerations ($\ddot{\theta}$mt, $\ddot{\theta}$gt, and $\ddot{\theta}$net in Figure 1(c) and (d)) were observed to be similar to those of the corresponding torques (MT, GT, and NT in Figure 1(a) and (b)) for both the upward and downward movements. In addition, the profiles of measured angular accelerations obtained from the second derivatives of the angular displacements ($\ddot{\theta}$m; indicated by the dotted grey lines in Figure 1(c) and (d)) for the upward and downward movements were sufficiently fitted to those of the net induced angular accelerations ($\ddot{\theta}$net; indicated by the solid black lines in Figure 1(c) and (d)). We temporally normalized the values of both $\ddot{\theta}$net and $\ddot{\theta}$m for all trials and computed the grand means of the absolute differences between $\ddot{\theta}$net and $\ddot{\theta}$m at specific time points. The grand means were determined to be 0.09 and 0.06 rad/s^2 for the upward and downward movements, respectively. These results indicate that the IAA properly reproduced the measured angular accelerations of the upward and downward movements.

A positive value of $\ddot{\theta}$net for both the upward and downward movements was an indication that $\ddot{\theta}$mt was higher than $\ddot{\theta}$gt, and vice versa in the case of a negative value of $\ddot{\theta}$net. Therefore, $\ddot{\theta}$mt contributed more to $\ddot{\theta}$net than $\ddot{\theta}$gt when $\ddot{\theta}$net was positive (as noted during the first half of the upward movement and the second half of the downward movement), while the contribution of $\ddot{\theta}$gt was greater when $\ddot{\theta}$net was negative (as noted during the second half of the upward movement and the first half of the downward movement).

Various other parameters were measured or determined by simulation (see section 2.3**. Data analysis**). The mean (±standard error) and median values of all the measured and simulated parameters for all participants are presented in Tables 1 and 2. The MD for the upward movement was observed to be significantly shorter than that for the downward movement ($t(7) = -2.616$, $p < 0.05$, $d = 0.390$). The AD and IADnet values for the upward movement were both significantly shorter

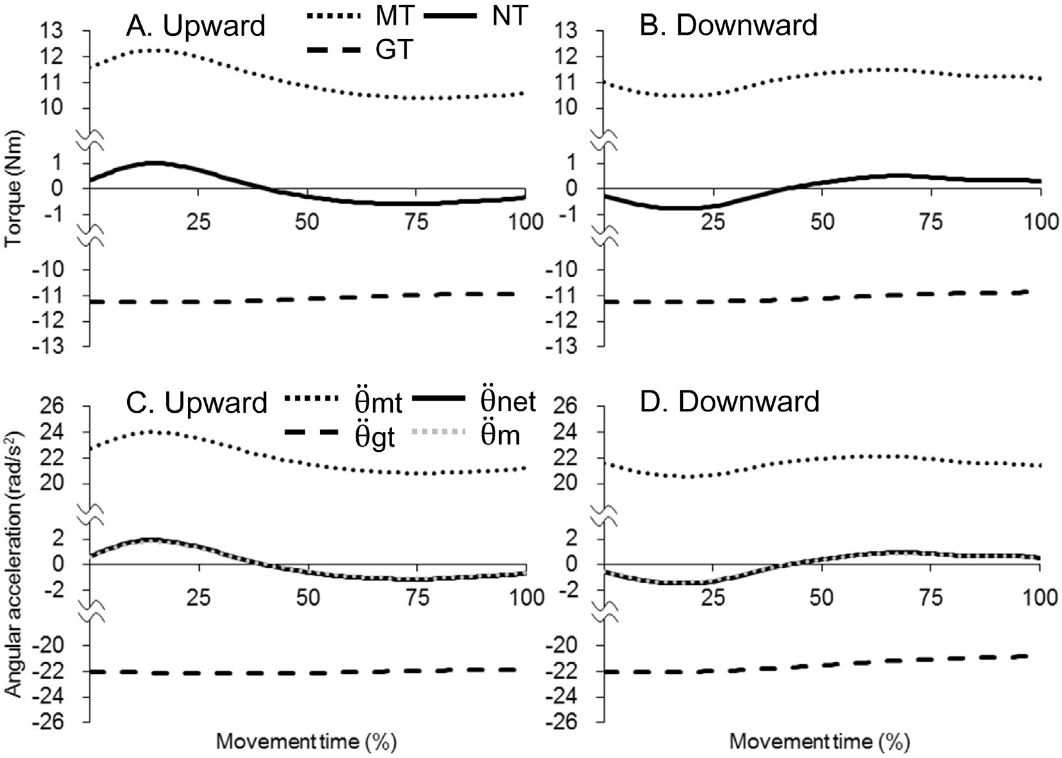

Fig. 1. Average torque and angular acceleration profiles for all participants with respect to the movement direction. Muscular torque (MT), gravitational torque (GT), and net torque (NT) are indicated by the dotted, dashed, and solid lines, respectively. The angular accelerations induced by MT ($\ddot{\theta}$mt) and GT ($\ddot{\theta}$gt), net induced angular acceleration ($\ddot{\theta}$net), and measured angular acceleration ($\ddot{\theta}$m) are indicated by the dotted black, dashed black, solid black, and dotted grey lines, respectively.

Table 1

Mean (standard error)/median values of the measured kinematic parameters of the vertical movements.

	Upward	Downward
MD (ms)*	1061 (88)	1165 (100)
AD (ms)*	435 (42)	475 (36)
DD (ms)[a]	538	591
PA (rad/s^2)*	2.14 (0.37)	1.77 (0.28)
DPA (ms)*	179 (23)	225 (26)
PD (rad/s^2)	1.61 (0.22)	1.45 (0.19)
DPD (ms)	743 (63)	801 (78)

MD: movement duration, AD: acceleration duration, DD: deceleration duration, PA: absolute peak angular acceleration, DPA: duration to peak angular acceleration, PD: absolute peak angular deceleration, DPD: duration to peak angular deceleration.

[a] Median values.

* $p < 0.05$.

Table 2

Mean (standard error)/median values of the simulated kinematic parameters of the vertical movements.

	Upward	Downward
IADnet (ms)*	434 (43)	478 (36)
IDDnet (ms)[a]	538	589
PIAnet (rad/s^2)*	2.26 (0.40)	1.88 (0.30)
DPIAnet (ms)*	179 (23)	226 (25)
PIDnet (rad/s^2)	1.70 (0.22)	1.50 (0.20)
DPIDnet (ms)	748 (61)	805 (74)

IADnet: net induced acceleration duration, IDDnet: net induced deceleration duration, PIAnet: absolute peak net induced angular acceleration, DPIAnet: duration to peak net induced angular acceleration, PIDnet: absolute peak net induced angular deceleration, DPIDnet: duration to peak net induced angular deceleration.

[a] Median values.

* $p < 0.05$.

than those for the downward movement (AD, $t(7) = -2.721$, $p < 0.05$, $d = 0.360$; IADnet, $t(7) = -2.903$, $p < 0.05$, $d = 0.393$). However, DD and IDDnet did not differ significantly between the two movement directions (DD, $z = -1.540$, $p > 0.1$; IDDnet, $z = -1.540$, $p > 0.1$). The values of PA and PIAnet for the upward movement were both significantly larger than those for the downward movement (PA, $t(7) = 2.497$, $p < 0.05$, $d = 0.402$; PIAnet, $t(7) = 2.425$, $p < 0.05$, $d = 0.377$). In addition, DPA and DPIAnet for the upward movement were significantly shorter than those for the downward movement (DPA, $t(7) = -3.189$, $p < 0.05$, $d = 0.662$; DPIAnet, $t(7) = -2.864$, $p < 0.05$, $d = 0.706$). There were no significant differences in the respective PD and PIDnet values for the two movement directions (PD, $t(7) = 1.375$, $p > 0.1$; PIDnet, $t(7) = 1.617$, $p > 0.1$). The same was true for the DPD, or DPIDnet values for the two movement directions (DPD, $t(7) = -1.093$, $p > 0.1$; DPIDnet, $t(7) = -1.081$, $p > 0.1$).

4. Discussion

We used IAA to investigate how MT and GT contribute to the kinematics of the movement. The purpose was to elucidate how the CNS generates a kinematic difference between upward and downward movements from the perspective of forward dynamic analysis. We found that, during the deceleration phase of an upward movement (the second half of the movement) and the acceleration phase of a downward movement (the first half of the movement), the angular acceleration induced by GT ($\ddot{\theta}$gt) contributed more to the generation of the net induced angular acceleration ($\ddot{\theta}$net) than the angular acceleration induced by MT ($\ddot{\theta}$mt). In addition, we observed that the difference between the angular acceleration profiles during upward and downward movements was primarily attributable to the difference between the corresponding angular acceleration profiles induced by MT. This suggests that the CNS controls muscular torque for vertical pointing movements accounting for gravitational torque. It should be noted that, in line with some previous studies [3, 4], a higher measured PA, shorter measured duration to its occurrence (DPA), and shorter measured AD were observed for the upward movement than for the downward movement. This indicates that IAA could reproduce previous measurements.

The IAA approach (a forward dynamic analysis approach) that was employed in the present study has been used for the analyses of human movements such as throwing [12] and quiet standing [13]. Several studies have examined the relationship between kinetics (torques) and kinematics for the multi-joint movements of throwing and quiet standing; this led to elucidation of the mechanisms of how these movements were kinetically generated. For example, Hirashima et al. [12] investigated how baseball players induced the kinematics at the trunk and upper limb joints and elucidated the differences in the kinetic mechanisms that induced the kinematics of proximal joint and those of distal joints. In the light of these findings of the previous studies, IAA is a powerful approach for elucidating the kinetic mechanisms of human movement. We cannot directly compare the findings of the previous studies with those of the present study, because the movement tasks are different between the previous (multi-joint task) and present (a single-joint task) studies. However, in the same way as in the previous studies, we examined and elucidated the kinetic mechanism for vertical pointing movement using IAA.

In the present study, IAA enabled evaluation of how the movement kinematics of the vertical pointing movement ($\ddot{\theta}$net) are induced by the MT and GT, which can be computed by inverse dynamic analysis. We observed the greater contribution of $\ddot{\theta}$gt to $\ddot{\theta}$net during the deceleration phase of the upward movement and acceleration phase of the downward movement. The results confirm the findings of a previous study [4]. Based on the measured kinematics data for upward and downward movements, Gaveau and Papaxanthis [4] suggested that the CNS utilizes gravity to brake upward and initiate downward movements. The results of the present study elucidating how GT contributes to the kinematics of movement support the suggestion by Gaveau and Papaxanthis [4], i.e., the utilization of gravity to brake upward and initiate downward movements, from the perspective of forward dynamic analysis, and expand the current understanding of vertical movement control mechanisms. Especially, the results of the present evaluation, which reveal the dominance of $\ddot{\theta}$gt during the deceleration phase of an upward movement and the acceleration phase of a downward movement, provide quantitative evidence of the considerations of the gravitational effect on the upper limb in a phase-specific manner with respect to the movement direction.

The strong relationship between the profiles of the net induced angular acceleration and the angular acceleration induced by MT might be attributable to the movement angle of 15°, which is relatively small considering that GT gradually increased from 0° to 90°. However, even on using an angle of 15°, changes in GT were observed (Figure 1(a) and (b)); therefore, its angle induced kinematic asymmetry between the upward and downward movements [15]. Additionally, we set the following simple experimental conditions in the present study; one degree of freedom (DOF), one movement velocity (a comfortable velocity for each participant), and one movement amplitude (15°). Therefore, we cannot conclude that the relationship between kinetics and kinematics for the vertical pointing movement applies to all the conditions of vertical pointing movement. Further studies using multiple DOFs, multiple movement velocities, and multiple movement amplitudes are required to better understand the contributions of MT and GT to kinematics in the vertical direction.

In conclusion, IAA was used to investigate how the kinematics of upward and downward movements of the upper limbs are generated, providing a forward dynamic analysis approach to elucidating the generation of kinematic differences between upward and downward movements by the CNS. It was found that, during the deceleration phase of an upward movement and the acceleration phase of a downward movement, the angular acceleration induced by GT contributed more to the generation of the net induced angular acceleration than that induced by MT. The results of the present study suggest that the CNS considers the effect of gravity to enable vertical movements of the upper limbs in a phase-specific manner.

Declarations

Author contribution statement

Shinji Yamamoto: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Keisuke Fujii: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Kisho Zippo, Masanobu Araki: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Keisuke Kushiro: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

[1] B. Berret, C. Darlot, F. Jean, T. Pozzo, C. Papaxanthis, J.P. Gauthier, The inactivation principle: mathematical solutions minimizing the absolute work and biological implications for the planning of arm movements, PLoS Comput. Biol. 4 (2008), e1000194.

[2] F. Crevecoeur, J.L. Thonnard, P. Lefèvre, Optimal integration of gravity in trajectory planning of vertical pointing movements, J. Neurophysiol. 102 (2009) 786–796.

[3] J. Gaveau, B. Berret, L. Demougeot, L. Fadiga, T. Pozzo, C. Papaxanthis, Energy-related optimal control accounts for gravitational load: comparing shoulder, elbow, and wrist rotations, J. Neurophysiol. 111 (2014) 4–16.

[4] J. Gaveau, C. Papaxanthis, The temporal structure of vertical arm movements, PLoS One 6 (2011), e22045.

[5] C. Papaxanthis, V. Dubost, T. Pozzo, Similar planning strategies for whole-body movements performed in the sagittal plane, Neuroscience 117 (2003) 779–783.

[6] C. Papaxanthis, T. Pozzo, P. Stapley, Effects of movement direction upon kinematic characteristics of vertical arm pointing movements in man, Neurosci. Lett. 253 (1998) 103–106.

[7] S. Yamamoto, K. Kushiro, Direction-dependent differences in temporal kinematics for vertical prehension movements, Exp. Brain Res. 232 (2014) 703–711.

[8] A.B. Le Seac'h, J. McIntyre, Multimodal reference frame for the planning of vertical arms movements, Neurosci. Lett. 423 (2007) 211–215.

[9] J. Gaveau, B. Berret, D.E. Angelaki, C. Papaxanthis, Direction-dependent arm kinematics reveal optimal integration of gravity cues, eLife 5 (2016), e16394.

[10] C. Papaxanthis, T. Pozzo, J. McIntyre, Kinematic and dynamic processes for the control of pointing movements in humans revealed by short-term exposure to microgravity, Neuroscience 135 (2005) 371–383.

[11] C. Papaxanthis, T. Pozzo, M. Schieppati, Trajectories of arm pointing movements on the sagittal plane vary with both direction and speed, Exp. Brain Res. 148 (2003) 498–503.

[12] M. Hirashima, K. Yamane, Y. Nakamura, T. Ohtsuki, Kinetic chain of overarm throwing in terms of joint rotations revealed by induced acceleration analysis, J. Biomech. 41 (2008) 2874–2883.

[13] S. Sasagawa, M. Shinya, K. Nakazawa, Interjoint dynamic interaction during constrained human quiet standing examined by induced acceleration analysis, J. Neurophysiol. 111 (2014) 313–322.

[14] R.C. Oldfield, The assessment and analysis of handedness: the Edinburgh inventory, Neuropsychologia 9 (1971) 97–113.

[15] R. Gentili, V. Cahouet, C. Papaxanthis, Motor planning of arm movements is direction-dependent in the gravity field, Neuroscience 145 (2007) 20–32.

[16] D.A. Winter, in: Biomechanics and Motor Control of Human Movement, fourth ed., John Willey & Sons, Inc., New York, 2009.