Functional Postural Responses in a Standing Man after Perturbation in Multiple Directions as Described by Net Joint Torques

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Abstract - *The objective of this study was to assess functional postural responses in a man by analyzing the net joint torques (NJT) in the ankles and the hips resulting from perturbations delivered in multiple directions. A total of eight subjects were quietly standing on two force platforms while an apparatus randomly delivered controlled perturbations at the level of pelvis in eight directions: anterio-posterior (AP), medio-lateral (ML), and four combinations of these principal directions. Perturbations were repeated five times in each direction for six conditions (i.e., three different perturbation strengths and three different feet orientations). The comparison of the averaged ankle sum NJT (AP) responses showed that the time courses of the responses elicited by a perturbation acting only in the AP plane were identical to those elicited by a combination of two corresponding AP and ML perturbations. In contrast the observed averaged ankle NJT (ML) responses did not follow the same similarity. The comparison of the averaged ankle and hip sum NJT (ML) responses revealed that the time courses of the responses elicited by a perturbation acting only in the ML plane were identical to those elicited by a combination of two corresponding AP and ML perturbations. These findings were consistent among all subjects and were invariable of experimental conditions.*

Keywords: postural responses, balance, multiple direction perturbations

1. Introduction

Postural control in standing man has been a subject of intensive research for the last few decades. Mostly, the research was directed into explanations of postural mechanisms utilized either in the anterio-posterior (AP) or medio-lateral (ML) directions [3,9]. The central issue was to identify control strategies of the central nervous system (CNS) by observing the kinematics, kinetics, and muscle synergies during quiet and perturbed stance. Two distinct patterns of balance recovery after perturbation induced in the AP direction has been qualitatively identified, namely "ankle" and "hip" balancing strategies [3]. For the ML direction it has been observed that the postural control is dominated by limb loading/unloading mechanism, which is predominantly under the control of hip abductors and adductors [7,9].

During standing CNS is coping with unexpected perturbations acting in arbitrary directions within the AP-ML space. Only in the last decade the scope of research has been extended to investigations into postural strategies and muscle synergies utilized after commencement of perturbations delivered in a combined AP-ML directions [1,2,6]. These studies focused on EMG responses of muscle groups previously identified as being significant for postural control; the perturbations were generated predominantly by moving or rotating standing platforms. The main conclusion of these studies was that the multi-directional postural control is much more complicated than unidirectional and as such can not be explained by a set of discrete muscle synergies as seen in postural responses following perturbations acting separately in either AP or ML directions [2,6].

It is difficult to elucidate the postural strategies utilized by CNS solely from the information provided by EMG measurements as the muscle synergies are highly variable and given postural strategy could be implemented by a variety of muscle synergies [4]. More consistent and repeatable information might be extracted from net joint torques (NJT) as they reflect overall muscle activity across joints of the multi-skeletal biomechanical system.

In this study our aim was to assess and analyze the NJT patterns acting in the ankle and hip joints after commencement of perturbations delivered in multiple directions within the AP-ML.

2. Methods

Eight male participants with no known neurologic or orthopedic disorders (mean age 31, SD 6.7 years; height 182, SD 8.8 cm; weight 75.8, SD 11.4 kg) participated in this study.

Perturbations were generated at the level of pelvis of a standing subject by means of a two degrees of freedom (DOF) servo-controlled mechanical apparatus named "Multi-purpose Rehabilitation Frame" (MRF). Subjects stood in such a way to have legs in parallel while being braced at the level of pelvis by the adjustable bracing system as shown in Fig. 1a. A detailed description of the MRF device is given in [5].

Perturbing torque pulses in duration of 200 ms were delivered either in one of four principal directions (Forward and Backward in the AP plane; Right and Left in the ML plane) or in one of four combinations of the principal directions (Forward & Right, Forward & Left, Backward & Right, Backward & Left) as shown in Fig.

1b. The subjects were instructed to stand relaxed prior to perturbation and attain the same posture throughout the trial after recovered from perturbation. The time instant of perturbation commencement was unknown to the subjects.

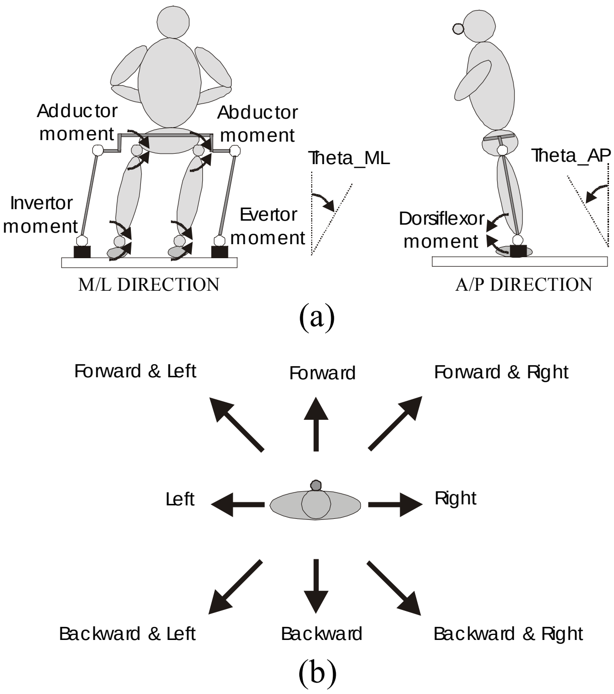

Fig. 1. a) Perturbing apparatus. NJT conventions and the inclinations of the MRF are illustrated. **b)** Perturbations were delivered in the eight directions: four principal (Forward and Backward in the AP direction and Left and Right in the ML directions) and four combinations of the principal directions (Forward & Left, Forward & Right, Backward & Left and Backward & Right).

Forty perturbations (five in each direction) were delivered in random order. This was repeated for six randomized trials under the following experimental conditions: for three different perturbation strength's (MIN, MED and MAX) and for three different feet orientations (I I, \ /, I /). For the first three conditions the orientation of the feet was the one subjects preferred (typically outward rotated for approx. 15 degrees) while for the last three conditions the feet were oriented: i) in parallel - I I; ii) widely outward rotated (from 30 to 40 degrees) - \ /; and iii) left foot oriented as in i) and right foot oriented as in ii) - I /. The perturbation strength for the last three conditions was MED. Prior to initiation of the study an introductory trial was undertaken where the amplitude of perturbation was varied. The amplitude where subjects could comfortably recover balance after the perturbation applied in Backward direction (by keeping feet flat on the blocks throughout the postural response) was selected as a MAX (MED=MAX/2, MIN=MAX/4).

All biomechanical recordings were initiated 500 ms prior to the onset of the perturbation and had a sampling duration of 3.5 s. Inclination angles of the MRF (shown in Fig. 1a) were collected using precision potentiometers (Spectrol, 157-9002-103) mounted to one of the 2-DOF joints of the MRF. Support surface reaction forces and moments were measured from two force plates (AMTI OR6-5-1000). From these forces and moments ankle (AP and ML projections) and hip (ML projection) NJT were calculated. NJT conventions are given in Fig. 1a. The kinematics of the legs in the ML plane was derived from Theta_ML (Fig. 1a) while the anthropometric data used in calculation of the hip NJT (ML projection) were adopted from [8]. All biomechanical data was sampled at 100 Hz and digitally low-pass filtered offline at 10 Hz using a zero phase-shift 10^{th}-order Butterworth filter.

The NJT responses acquired during a trial were averaged across each direction. A mean value of NJT for the period 500 ms prior to perturbation was calculated and subtracted from the same NJT.

3. Results

A complete set of representative ankle NJT (AP and ML) and hip NJT (ML) responses obtained under the experimental condition MAX for one of the subjects is displayed in Fig. 2. Fig. 2a shows ankle NJT (AP) responses. It can be seen that the responses to perturbation acting in the Right and Left directions are very small. Responses after perturbation in Forward direction are characterized by activity in both ankles. When a combined perturbation is delivered in the Forward & Left direction the left ankle NJT dominates while in case of Forward & Right direction the right ankle NJT is higher. When looking at the ankle sum NJT we can observe similarity between the responses after perturbations delivered in Forward, Forward & Left and Forward & Right direction. All three responses are superimposed at the right-hand side of the upper row. Indeed we can see that the responses are almost identical during the first 800 ms after the perturbation commencement. Similar observation holds for the responses elicited by perturbations acting in Backward, Backward & Left and Backward & Right directions. Fig. 2b shows ankle NJT (ML) responses. The left ankle, right ankle and the sum NJT vary with different perturbation directions. No observation, similar to the ankle NJT (AP) responses can be drawn. Fig. 2c shows calculated hip NJT (ML) and ankle and hip sum NJT (ML) responses. It can be seen that the responses to perturbation acting in the Forward and Backward directions are small. Responses following the perturbation in Left direction are characterized by activity in both hips. When a combined perturbation is delivered in the Forward & Left direction the left hip NJT dominates while in case of Backward & Left the right hip NJT is higher. When looking at the hip sum NJT we can observe similarity between the responses elicited by perturbations delivered in Left, Forward & Left and Backward & Left direction, however, it can be

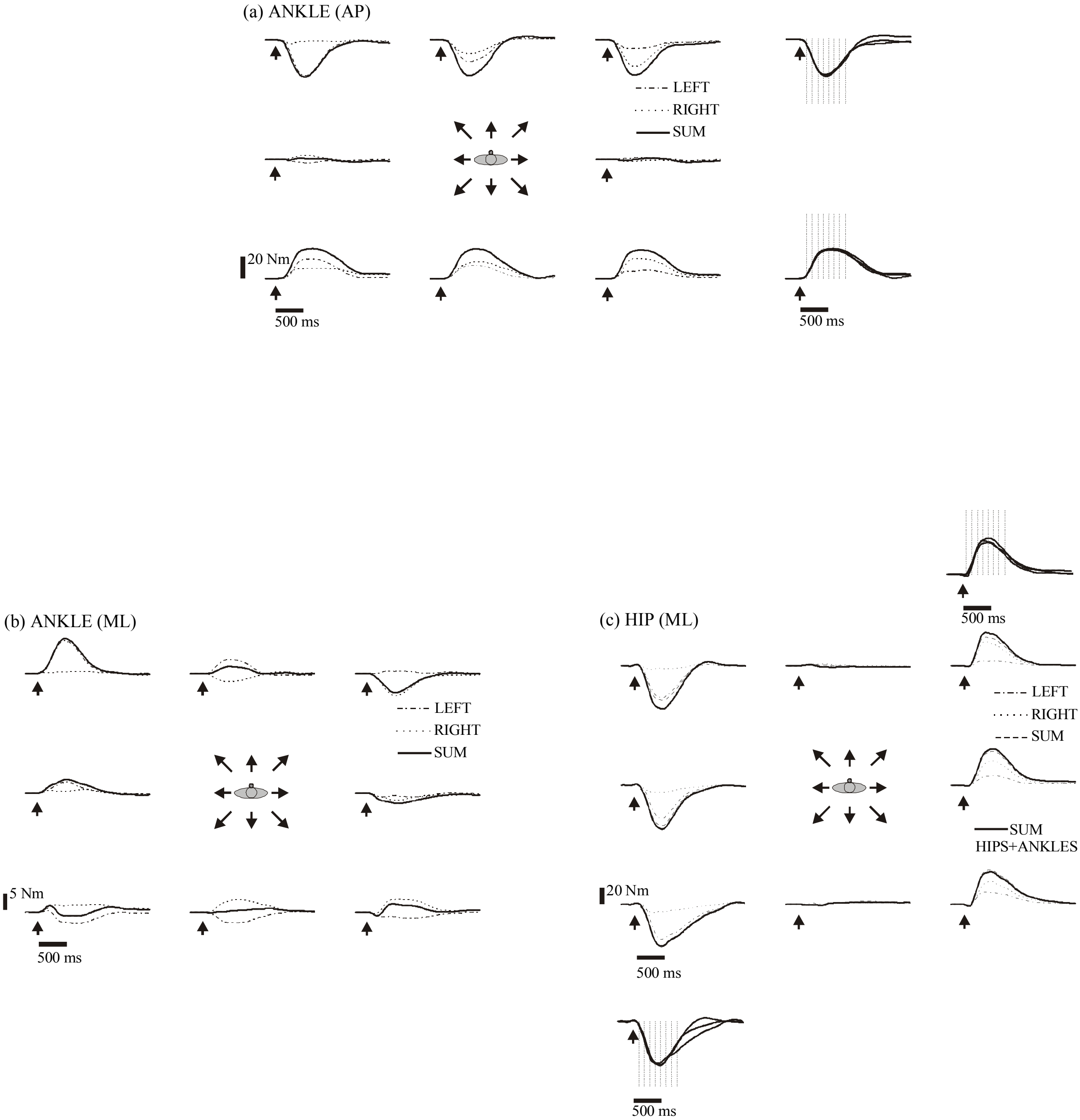

Fig. 2. The representative NJT responses (subject #3, experimental condition MAX). An arrow shows a time instant of perturbation commencement. **a)** The ankle NJT (AP) responses are shown for each perturbation direction. At the right hand side the ankle sum NJT (AP) are plotted together for the perturbation directions: Forward, Forward & Left, Forward & Right (upper row) and Backward, Backward & Left, Backward & Right (lower row). The vertical dotted lines (equally spaced at 100 ms) denote the values that were used with the three-way repeated measures ANOVA. **b)** The ankle NJT (ML) responses are shown for each perturbation direction. **c)** The hip NJT (ML) responses are shown for each perturbation direction. The ankle and hip sum NJT (ML) are plotted together for the perturbation directions: Left, Forward & Left, Backward & Left (upper right corner) and Right, Forward & Right, Backward & Right (lower left corner). The vertical dotted lines (equally spaced at 100 ms) denote the values that were used with the three-way repeated measures ANOVA.

seen that the maximal amplitude of the responses differ. If we look at the sum of NJT responses in all four joints (ankle and hip NJT (ML)) then the similarity improves. All three responses are superimposed at the right-hand side of the upper row. Similarly, as in the ankle sum NJT (AP) we can see that the responses are almost identical during the 800 ms after the perturbation commencement. Similar observation holds for the responses elicited by perturbations acting in the Right, Forward & Right and Backward & Right directions.

The ankle sum NJT (AP) and the ankle and hip sum NJT (ML) responses were examined in a three-way repeated measures ANOVA. The first factor was the differences between the following ankle sum NJT (AP) responses: Forward – Forward & Left, Forward – Forward & Right, Backward – Backward & Left, Backward – Backward & Right; and the differences between the following ankle and hip sum NJT (ML) responses; Left – Forward & Left, Left – Backward & Left, Right – Forward & Right, Right – Backward & Right. The second factor was repeated measures of these differences at eight succeeding time instants starting at 100 ms after perturbation commencement and following each 100 ms as shown in Fig. 2a and 2c. The third factor was the experimental conditions. There were no statistically significant differences for the three way interaction among factors ($P = 0.92$).

4. Discussion

The results presented in this study can be summarized as follows. The ankle sum NJT (AP) responses when recovering from the combined perturbation (either in the directions Forward & Left, Forward & Right or in the directions Backward & Left, Backward & Right) were identical to the ones assessed after the perturbation acted only in a principal direction (either Forward or Backward). As a consequence of this choice, made by the CNS, the ankle sum NJT (ML) responses, depending substantially on the orientation of feet as well as the strength of perturbation, were determined. The ankle and hip sum NJT (ML) responses when recovering from the combined perturbation (either in the directions Forward & Left, Backward & Left or in the directions Forward & Right, Backward & Right) were identical to the ones assessed after the perturbation acted only in a principal direction (either Left or Right). This means that the CNS was aware of the situation at the ankles and consequently, the hip NJT (ML) were determined in such a way that the sum of the parallelogram (composed of both ankles and hips in the ML) was equal across the comparable directions. The findings regarding the ankle sum NJT (AP) and ankle and hip sum NJT (ML) responses were invariable of the perturbation strength and feet orientation as suggested by the results of the statistical analysis.

The findings of this study lead to the conclusion that the postural responses, following a perturbation delivered simultaneously in two planes, result from a control strategy that transforms multivariable control problem into two decoupled univariable problems. These are i) the control of balance in the AP plane and ii) control of balance in the ML plane.

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