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Does the centre of mass remain stable during complex human postural equilibrium tasks in weightlessness ?

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Abstract

In normal gravity conditions the execution of voluntary movement involves the displacement of body segments as well as the maintenance of a stable reference value for equilibrium control. It has been suggested that centre of mass (CM) projection within the supporting base (BS) is the stabilised reference for voluntary action, and is conserved in weightlessness. The purpose of this study was to determine if the CM is stabilised during whole body reaching movements executed in weightlessness. The reaching task was conducted by two cosmonauts aboard the Russian orbital station MIR, during the Franco-Russian mission ALTAIR, 1993. Movements of reflective markers were recorded using a videocamera, successive images being

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reconstructed by computer every 40ms. The position of the CM, ankle joint torques and shank and thigh angles were computed for each subject pre- in- and post-flight using a 7-link mathematical model. Results showed that both cosmonauts adopted a backward leaning posture prior to reaching movements. Inflight, the CM was displaced throughout values in the horizontal axis three times those of pre-flight measures. In addition, ankle dorsi flexor torques inflight increased to values double those of pre- and post-flight tests. This study concluded that CM displacements do not remain stable during complex postural equilibrium tasks executed in weightlessness. Furthermore, in the absence of gravity, subjects changed their strategy for producing ankle torque during spaceflight from a forward to a backward leaning posture.

KEY WORDS : Posture, Movement, Whole body reaching, Centre of mass, Weightlessness.

Introduction

Under normal gravity conditions the execution of voluntary movement involves the displacement of body segments as well as the maintenance of a stable reference value for equilibrium control. A stable reference value, providing a base for the execution of voluntary action, has been suggested as being the head (Pozzo et al.,1990), the position of a segment in space (Droulez & Berthoz,1986) or limb verticality (Lacquaniti et al.,1984). However, the idea that the projection of the centre of mass (CM) within the base of support represents the stabilised reference for voluntary action, seems to be a widely accepted one (Bouisset & Zattara,1981 : Crenna et al.,1987 : Mouchnino et al.,1992).

This idea, of the CM as a stabilised reference, has been upheld in conditions of weightlessness. Massion et al.,(1993 ; 1996) have shown that during forward and backward upper trunk movements, axial synergies, opposing displacements of the hip, trunk and knee, are preserved during spaceflight, the configuration of body segments being readjusted to keep CM projection constant within the BS. More recently, Mouchnino et al.,(1996) have shown with lateral leg raising movements during parabolic flight, that despite a suppression of an anticipatory CM shift, CM stabilisation is preserved by opposite movements of the trunk and leg. A previous study of arm raising during prolonged spaceflight (Clément et al.,1984) has also shown that hip stability is preserved, suggesting that postural control mechanisms function mainly to stabilise the trunk, as in terrestrial conditions (Gurfinkel et al.,1976,1981).

Recently however, during a whole body reaching task executed in normal gravity, it has been suggested that the CM does not represent a stable reference value for postural control (Stapley et al. in press). Increasing speed of reaching was preceded by anticipatory postural adjustments (APAs) that displaced the CM rather than ensuring its' minimisation, has been suggested during arm raising (Bouisset & Zattara,1981). Despite the presence of axial synergies, the CM was displaced in the AP plane to values of up to 95% of total BS length.

In normal gravity conditions, muscular and gravitational forces have been shown to create appropriate postural and dynamic conditions for CM acceleration during the initiation of human gait (Lepers & Breniére,1995). Assuming the body to be of an inverted pendular configuraton rotating about the ankle axis, net torque (M_{net}) for acceleration of the CM in the sagittal plane is equal to : $M_{net} = M_A + M_{grav}$, where M_A = accelerational (muscular) and M_{grav} = gravitational torque. Using this interpretation, we have previously stated that during whole body reaching the gap between the CM and the centre of pressure produced increased net ankle dorsi flexor joint torque when objects were placed further, subjects using both muscular and gravitational torques for horizontal and vertical CM displacement (Stapley et al. 1996). In weightlessness however, gravitational torques are lacking, the sole source of torque for the initiation of whole body reaching being muscular. Thus, weightlessness provides a good opportunity to evaluate the participation of muscular torques to initiate whole body reaching.

Finally, Pozzo et al.,(1995) have noted an initial backward leaning posture preceding whole body reaching inflight, suggesting it to be a strategy whereby subjects prepared movement execution by stretching flexors of the ankle. This is in contrast to previously recorded forward leaning postures, which were interpreted as compensation by flexor muscles of the lower leg to increased activity of extensors in the absence of gravity (Clément et al.,1984).

This study thus attempted to determine if, in weightlessness subjects stabilise the CM, as has been demonstrated during other axial synergy movements. Through the recording of initial shank and thigh angles we also wished to outline postural strategies used by subjects to produce required net ankle joint torques, in the absence of gravitational components. This in turn , may add weight to ideas that postural adjustments are used to initiate CM displacements, via muscular action at the ankle.

Methods

Subjects

The reaching task here belonged to the "Synergy" experiment performed aboard the Russian orbital station MIR, during the Franco-Russian spatial mission ALTAIR of 1993. Experiments were conducted pre-, in-, and post-flight upon two cosmonauts, here called C1 and C2. C1 had never flown before, whereas C2 was undertaking his third spaceflight. The durations of spaceflight were 21 and 180 days for C1 and C2, respectively. Data will be presented 60 days before the flight (PF-60) for both cosmonauts. In-flight tests (marked FD*x* , *x* being the flight day) took place on FD5, FD10, FD13, and FD20 for C1 and FD6, FD9, and FD20 for C2. Post-flight tests were conducted one (R+1) and six (R+6) days after landing for C1 and three (R+3) and five (R+5) days after landing for C2.

Protocol

Cosmonauts, with their feet strapped to the supporting surface, were asked to begin in what they regarded as an upright position. With their hands at the level of their waists and behind the vertical body axis, they were instructed to reach and grasp an object (a box 40x15x25cm weighing 500g), lift it to shoulder height, pause and replace it in its' original position, and return to their starting position. For the purpose of this study, only the first reaching phase was analysed. The object was placed at one of two positions 5 (D1) and 45cm (D2) from the cosmonauts toes. Cosmonauts conducted 4 series of 5 trials each separated by a pause of at least 1 minute. Movements of retro-reflective markers placed on the cosmonauts body were recorded by a video camera placed at 2m from their sagittal planes. Markers were placed at 11 anatomical sites including the head (vestibular apparatus - the Frankfort plane), the trunk, arm, leg, and foot. Successive images at 25Hz were digitised using a computer in order to calculate positions of body segments every 40ms. Kinematic derivatives (velocity and acceleration) were computed in both translation and rotation.

Data Analysis

Raw data was filtered using a Butterworth filter. Movement onset (*t0*) was taken as the moment at which derived curvilinear velocity (of movements in both X and Y axes), of marker 2 (consistently the first to move) exceeded 10% of its' peak during reaching. The position of the body's CM was calculated in the sagittal plane using a seven segment, rigid mathematical model. The model consisted of the following appendicular and axial body segments : head-neck, upper trunk, abdomen-pelvis, thigh, shank, upper arm and forearm. Foot position was assumed to be bilaterally symmetrical and stationary. Positions of segment ends were taken from recorded horizontal and vertical displacement values. Using the model, the position of the CM of a *i*th segment with co-ordinates X_i, Y_i was calculated using the following formulae :

$$X_i = X1_i + l_i(X2_i - X1_i) \text{ and } Y_i = Y1_i + l_i(Y2_i - Y1_i),$$

where $X1_i, Y1_i, X2_i, Y2_i$ = co-ordinates of segment ends, l_i = the ratio between the distance of the proximal marker to the segments' CM and its' length.

Coordinates X and Y of the total body CM were thus calculated using the formulae :

$$X = \sum m_i X_i / \sum m_i \text{ and } Y = \sum m_i Y_i / \sum m_i \ ,$$

m_i being the mass of the *i*th segment.

Anthropometric segment parameters including their masses, moments of gyration and positions of the CM, taken from Winter,(1990), were used to determine both whole body CM position, as well as torques and forces acted upon joints. The model was treated as an open loop kinematic chain starting with the upper trunk, applying Lagrangian equations of motion to the observed motion of any one-joint segment. By systematically considering each segment, equations for force and torque were :

$$\sum_j \mathbf{F}_{ij} = m_i \mathbf{a}_i \text{ and } \sum_j M_{ij} = J_i \omega_i \ ,$$

where $\mathbf{F}_{ij}, M_{ij}$ = vectors of force and scalar torque acted upon joint *j* of the segment *i*, respectively. m_i , J_i , $\mathbf{a}_i$, ω_i represent respectively, segment mass, its' moment of gyration relative to its' CM, a vector of CM acceleration, and angular acceleration of the segment around an axis perpendicular to the plane of motion. A segments' CM acceleration $\mathbf{a}_i$ and its' angular acceleration ω_i were calculated using X and Y co-ordinates, its' length l, l_i and accelerations of proximal and distal ends.

In the present study, as subjects executed movements in a leftward direction, torques with a positive sign were taken as dorsi-flexor (flexion) and a negative one, plantar flexor (extension). Analyses were based only upon net torques (the sum of gravitational and inertial components) produced around the ankle joint. Thus, in weightlessness it was necessary to consider only inertial (muscular) torques as net joint torques exerted around the ankle. Peak dorsi flexor torques were derived from average ankle joint torques calculated over a period of 500 ms preceding the onset of head marker displacement.

Results

Initial posture

Initial erect posture was determined during the initiation phase of whole body reaching on the basis of vertical spatial angles made by shank and thigh segments with respect to the supporting surface. Recorded pre-flight shank angles were 167.5° (±0.6) and 167.8° (±0.6) for C1 and 171.7° (±0.6) and 171.7° (±1.3) for C2, respectively at first and second reaching distances. These were accompanied by the following pre-flight thigh angles : 179° (±1.3) and 178.5° (±0.7), C1 and 175.4° (±1.4) and 174.1° (±1.7), C2 for D1 and D2 respectively. Figure 1 shows trends shown by both shank and thigh angles pre-, in- and post spaceflight for cosmonauts C1 and C2. These two spatial angles are represented graphically by the stick figure at the centre right.

Interesting trends emerged concerning shank and thigh angles preceding whole body reaching. C1 (upper part of the figure 1) clearly shows that the initial angle of the shank segment

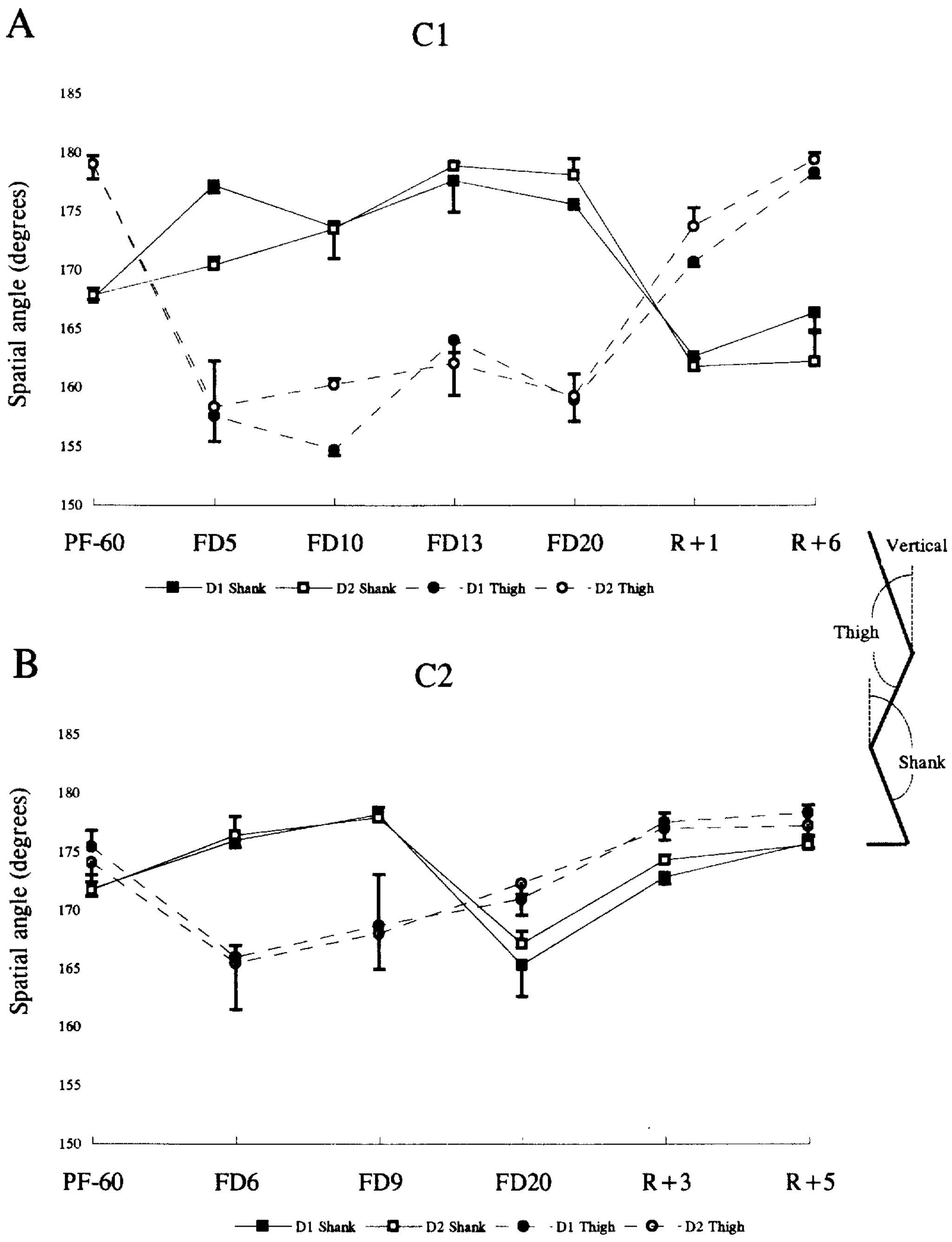

Figure 1. Shank and thigh spatial angles

increased during all flight days from pre-flight values for both reaching distances. Once returned to earth, C1 noticeably decreased the angle made by the shank segment with the subjective vertical. Thigh angles however, showed an inverse pattern to those demonstrated by the shank segment. From pre-flight values that neared the vertical, inflight thigh angles decreased by up to 20° for C1, but returned to pre-flight values during post-flight recording sessions.

Increases in shank angles also occurred during the early stages of spaceflight for C2, but showed decreases at FD20 from FD9 values, being slightly less than pre-flight values. On returning to earth however, C2 increased shank angles to approximately those recorded pre-flight (see Figure 1 bottom). C2 thigh angles also showed decreases during the early stages of spaceflight from pre-flight values, but neared pre-flight values at FD20. Post flight measures were approximately similar to pre-flight ones.

In terms of differences in spatial angles of shank and thigh segments, both C1 and C2 showed no differences between first and second reaching distances during pre-, in- and post-flight recording sessions. Results suggested however, that during spaceflight there was a tendency for cosmonauts to progressively bring the shank segment to the vertical, whilst at the same time flexing the thigh segment with respect to the trunk, thus decreasing its' spatial angle. This resulted in cosmonauts somewhat 'sitting back' on their axis of rotation (the ankle), and the projection of their CM being further back within foot length.

Horizontal and vertical centre of mass displacements

Figure 2A shows block graphs of horizontal CM displacements pre-, in and post-flight for cosmonauts 1 and 2. The primary observation corroborates results from eight subjects tested in normal gravity conditions outlined in a recent paper (Stapley et al. 1996), that CM displacements largely increased between reaching distances D1 and D2 during pre- and inflight periods of the mission for both cosmonauts. It was however, only pre- and post-flight horizontal CM amplitudes that were similar to those previously reported in non-cosmonaut subjects.

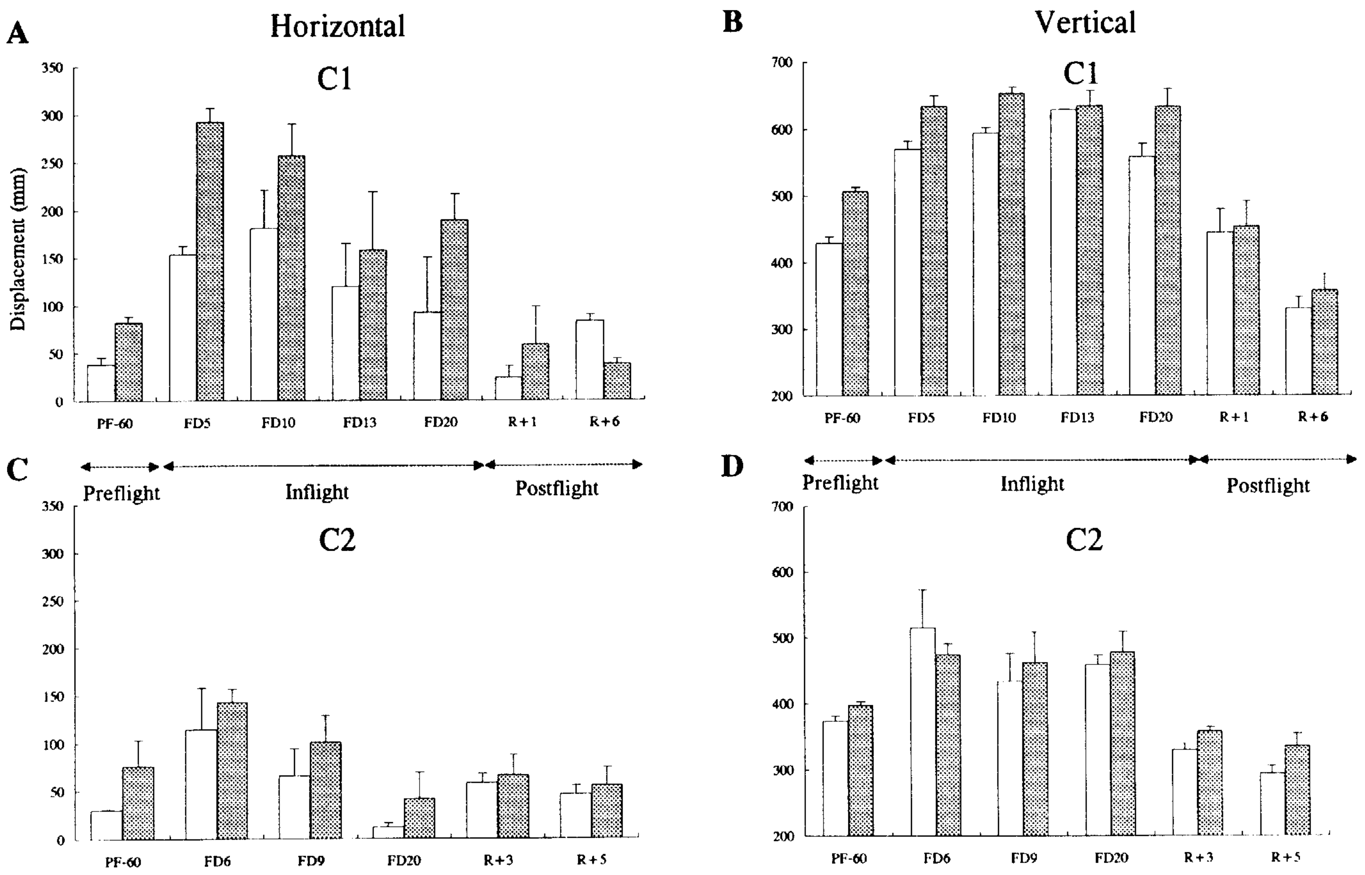

Figure 2. Displacements of the centre of mass

During early stages of spaceflight, C1 showed horizontal CM amplitudes that greatly increased to values almost three times those recorded pre-flight. These values decreased throughout the flight, although remaining approximately double those of pre-flight values on days 13 and 20. CM horizontal amplitudes resembled pre-flight ones when C1 returned to earth (see Figure 2A)

C2 showed similar increases in horizontal CM amplitudes during early stages of spaceflight to C1. CM amplitudes increased from 30.1 ±0.8 mm (D1) and 76.1 ±27 mm (D2) on PF-60 to 114.3 ±9.1 mm (D1) and 142.6 ±14 mm (D2), on FD6 and 65.6 ±39.8 mm (D1) and 100.5 ±32.7 mm (D2), on FD9. On FD20 however, C2 showed CM amplitudes smaller than those recorded pre-flight. C2 also showed CM amplitudes on return days 3 and 5 similar to values recorded PF-60, (see Figure 2C).

During spaceflight, both cosmonauts showed significantly greater vertical CM amplitudes for both reaching distances, compared to pre-flight values (see Figures 2B and D). As previously seen with horizontal CM displacements, vertical CM amplitudes produced whilst cosmonauts reached objects at D2 were greater than those at D1. Interestingly, in contrast to horizontal CM displacement that decreased progressively inflight, vertical displacements remained constant throughout spaceflight. Upon returning to earth, cosmonauts demonstrated vertical CM amplitudes that were similar to pre-flight values.

Ankle joint torques

Figure 3 shows values of net ankle joint dorsi flexor torques for C1 and C2, pre-, in- and post-spaceflight, whilst reaching to objects placed at the two distances. It should be noted that values were always greater when cosmonauts reached objects at D2 than D1, regardless of experimental testing session. For C1, Figure 3A clearly shows that dorsi flexor torques at the

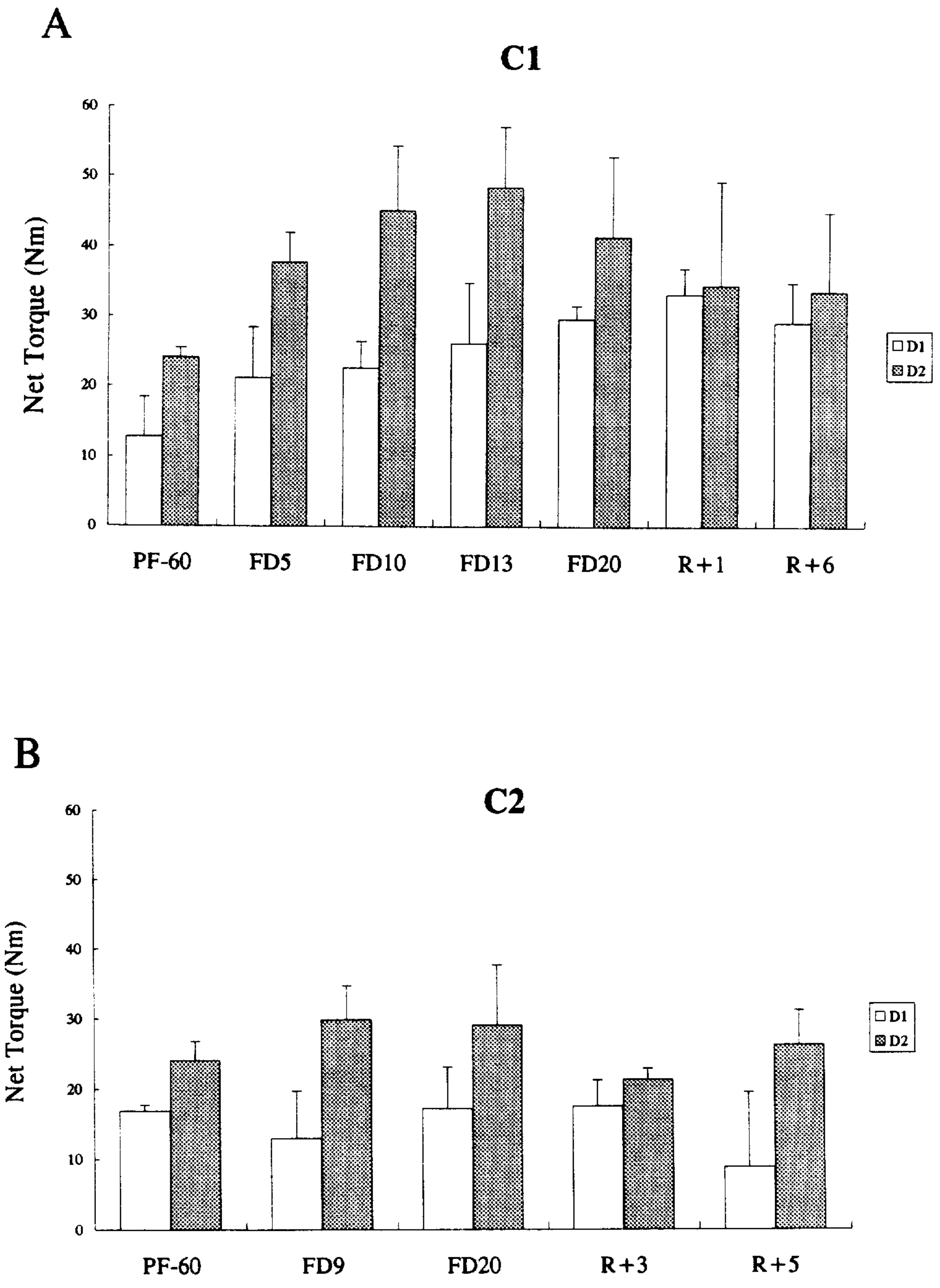

Figure 3. Ankle dorsi flexor torques

ankle progressively increased from pre-flight values during spaceflight. Indeed, on the 13th day, ankle torques were almost double those recorded pre-flight (26 ± 8.6 Nm - D1 : 48.2 ±8.7 Nm- D2). Once returned to earth however, C1 continued to produce ankle torques that exceeded those recorded pre-flight, decreasing only slightly at R+6.

C2 showed similar trends in dorsi flexor torques but with a somewhat less marked increase than C1 did. Nevertheless, a different pattern may be noted in C2 compared to C1 at D1 (decreases at FD9). Post-flight values were not different from pre-flight ones at R+3 and R+5, regardless of reaching distance.

Discussion

A number of interesting observations emerge from results presented above. The first concerns the initial posture adopted by both cosmonauts in the period of initiation of whole body reaching. We recorded initial postures that were the opposite to those previously seen during arm raising (Clément et al.,1984 : Clément & Lestienne,1988) or forward bending (Massion et al.,1993) in weightlessness. In these studies, despite differing methods of evaluation (e.g. trunk angle or malleolus-shoulder angle), subjects were recorded to lean forwards from the vertical in-flight. In the present study, cosmonauts increased the angle of the shank segment with the vertical, at the same time flexing the thigh segment in relation to the trunk. This would have resulted in a backward projection of the CM over the malleolus axis, and a backward leaning posture confirming and quantifying results of Pozzo et al. (1995).

What is the explanation for such a backward leaning strategy during the execution of whole body reaching? Results in normal gravity have shown an anticipatory shift of the centre of pressure forwards within the base of support in order to create a difference between it and the CM and thus adequate ankle joint torques. Of course, this strategy assumes that a certain percentage of forward thrust created by ankle torques is derived from the forces of gravity, underlining the importance of gravity in movement initiation (Lepers & Brenière, 1995). In weightlessness however, as gravitational torques are lacking, subjects are obliged to use a different strategy for producing rotational displacements of segments and the CM about the malleolus axis. This may have a specific functional significance. We propose that for forward oriented reaching movements in weightlessness, force can be generated only by the use of footstraps attaching the feet to the cabin floor. Here, backward leaning strategies involve the shank and thigh segments stretching elastic properties of the lower limb postural muscles (e.g. tibialis anterior - TA), in order to create adequate forward thrust. This would also agree with previous suggestions of Pozzo et al. (1995).

Our results also showed that CM displacements in both axes were not conserved from normal gravity conditions, but largely increased during spaceflight. This seems to contradict previous ideas of Lestienne & Gurfinkel,(1988) that CM regulation is independent of gravity conditions, and other findings that axial synergy reconfigurations act to keep the projection of the CM constant with respect to the feet (Massion et al.,(1993). When compared to findings at D2 in normal gravity conditions where CM displacements reached up to 95% of the base of support length, horizontal CM amplitudes recorded in weightlessness would suggest that the CM may indeed have left the base of support, and therefore did not remain stabilised during whole body reaching.

The final point is that C2 in comparison to C1 showed smaller increases in spatial angle configuration, horizontal and vertical CM displacements and ankle dorsi flexor torques. It is important to note that C2 had participated in two previous space flights. Hence, it may be that C2 had learned to use a new strategy for target attainment, being less dependent upon shank and thigh ankle reconfiguration, and thus did not produce as large dorsi-flexor ankle torques as C1. C1 however, showed considerable increases in ankle dorsi-flexor torques and was highly dependent upon this new strategy to reach the target. It is likely that C2 had learned to correctly use the footstraps, increasing knee joint torque to fulfill what normally would be achieved by gravity force. These findings thus cast some doubt upon the theory that there were conservative processes at work (Clément et al.,1984: Lestienne & Gurfinkel,1988) during whole body reaching movements in-flight. These have been described as highly stable, pre-established reference systems based on everyday experience movements. This may be concluded as C2 seemed to have maintained a new strategy from previous experience to achieve forward oriented movements. Analysis of knee flexor torques may help to clarify these ideas by examining pulling forces exerted on the footstraps produced by subjects in weightlessness. It is clear however that, upon their return to earth, cosmonauts adopted a forward leaning posture, as recorded pre-flight, thus using gravity force to initiate reaching movements, which in turn was reflected in decreased ankle dorsi flexor torque and CM displacement.

In conclusion, this study has shown that during spaceflight cosmonauts adopt a backward leaning posture which may be a strategy to stretch elastic properties of the muscle and increase dorsi flexor ankle torques. Indeed, these findings show that in the absence of gravity, commonly used in terrestrial conditions to forward oriented movement (Lepers & Brenière, 1995), muscular dorsi flexor torques produced at the ankle are substantially increased.

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