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POSTURAL REORGANIZATION FOLLOWING LOWER LIMB AMPUTATION

Possible Motor and Sensory Determinants of Recovery

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ABSTRACT. **Postural control was assessed in persons with a unilateral lower limb amputation before and after their rehabilitation. The centre-of-pressure fluctuations during quiet upright standing on a dual-plate force platform were registered with and without visual information in order to identify relevant determinants of balance restoration. In addition, static (weight distribution) as well as dynamic (control activity) asymmetry characteristics were examined. Besides a small improvement in balance control with full visual information (fore-aft sway, $p<0.06$; lateral sway, $p<0.05$), there was a major decrease in visual dependency (fore-aft and lateral sway, $p<0.05$) indicating a somatosensory re-integration process. Postural asymmetry in comparison with matched control subjects was most apparent and only significant in dynamic terms and remained constant across rehabilitation. It is concluded that after a lower limb amputation a central reorganization of postural control takes place, in which sensory determinants of motor recovery may play a critical role.**

Key words: amputation, posture, vision, proprioception, learning.

Of all the research which has been focused on stance in subjects with lower limb amputation, relatively few studies have dealt with the control characteristics of maintaining posture with a lower limb prosthesis (1, 4, 6, 7, 10, 11, 32). Even fewer studies have focused on the restoration of balance control after a lower limb amputation (7, 10). Balance in persons with lower limb amputation has, however, been recognized as a relevant clinical problem, particularly during the early phases of rehabilitation (18, 19).

Nevertheless, reduced balance control in subjects with lower limb amputation has not been unequivocally demonstrated in conditions with full perceptual information (4, 6, 7, 11). On the other hand, increased visual control of posture seems to be a more characteristic consequence of both below- and above-knee amputation, caused by the reduced availability of somatosensory information (4, 6, 11).

Little is known about postural control during the early phases following lower limb amputation. Gauthier-Gagnon et al. (7) reported a diminution of visual dependency in five subjects with below-knee amputation who had been trained with auditory feedback from a limb load monitor. However, this was not found in a control group of six subjects who had received traditional training. There was no decrease in sway during quiet stance with the eyes open in either group.

Although a lower limb amputation is primarily a peripheral disorder, a central reorganization must take place to adapt to the peripheral sensory and motor impairments (10). By studying balance recovery, information can be obtained about the most critical determinants of sensorimotor reorganization after lower limb amputation to improve assessment procedures and rehabilitation programmes.

Therefore, quiet standing was examined in a heterogeneous group of subjects with unilateral lower limb amputation before and after a traditional training programme. The basic level of balance control efficiency was assessed, as well as the degree of visual dependency to examine the contribution of motor and sensory processes to the central reorganization following lower limb amputation. Some preliminary data on this issue were reported earlier (8).

In addition, it was evaluated whether balance restoration would coincide with a reduction in postural asymmetry. Such asymmetry is generally expressed in terms of weight bearing (static asymmetry) (16, 29), although the relevance of weight distribution between the feet for monitoring balance skills in persons with lower limb amputation is still unclear (7, 28, 30). In this study, postural asymmetry was also assessed in dynamic terms (dynamic asymmetry) by recording the centre-of-pressure fluctuations under each foot. In this way, the compensatory control activity of the non-amputated limb was evaluated before and after the rehabilitation process.

SUBJECTS AND METHODS

Subjects

The amputation group ($n=10$) was aged 25 to 84 years (mean age 67.7 ± 18.1) and consisted of 7 males and 3 females with either a below- ($n=4$), a through- ($n=3$) or an above-knee ($n=3$) amputation. The four patients with a below-knee amputation had a vascular (diabetic) cause of amputation. Of the six patients with a through- or above-knee amputation, three subjects had a non-vascular and three subjects had a vascular (non-diabetic) cause of amputation.

During a period of eight months, persons with a recent unilateral limb amputation above the ankle and below the hip joint participated in the study. Subjects suffering from serious cognitive (e.g. disorders of memory or attention) or perceptual (eg. cataract or visual field loss) deficits were excluded, as well as those suffering from pain problems. In addition, a group of ten healthy subjects were tested, matched for age and gender (mean age 65.6 ± 16.5).

Equipment

Balance measurements were made with a firmly secured force platform which consisted of two separate aluminium plates, each placed on three force transducers (hysteresis and non-linearity $<1\%$) recording the vertical ground reaction forces. The force platform was connected to a microprocessor, which determined the virtual centre of the ground reaction forces at a sampling rate of 20 Hz and with a maximum error of ±1 mm in both directions of sway. The coordinates of this centre-of-pressure (CP) were led through a digital low-pass 5-Hz filter to eliminate erroneous readings due to noise.

Procedure

During the balance recordings, the subjects stood erect on the force platform with their feet against a foot frame (medial sides of the heels 8.4 cm apart; each foot toeing-out at a 9° angle from the sagittal midline). The subjects were repeatedly instructed to stand as still and symmetrically as possible with their hands folded behind their back.

Each test procedure consisted of three conditions—standing with the eyes open, with blurred vision (wearing milky-white spectacles preventing visual anchoring) and with the eyes closed (reinforced by closed dark spectacles). With their eyes open, the subjects faced a white wall at a distance of 1.5 meters. The blurred-vision condition was employed, in addition to the eyes-closed condition, because there is evidence that the effect of discongruent visual input is different from the effect of visual suppression (17, 21, 25).

In every condition, balance was recorded for 20 sec with at least one minute's rest between conditions. A fixed sequence of tests—eyes open, blurred vision, eyes closed—was employed, so that order effects were kept constant. A complete sample of 20-sec registration represented postural control in each condition.

Each balance assessment consisted of two consecutive test procedures. In all the patients, balance was assessed one or two days after the first training with the definitive type of prosthesis (start of rehabilitation) and repeated just before the completion of the training programme (end of rehabilitation). The matched control subjects were tested once, with bare feet, to obtain reference values.

Before the start of rehabilitation, every patient was given exercises with an airboot for a variable period from three to six weeks. The period between the start and the end of rehabilitation varied considerably between subjects from three to fourteen weeks (mean 10.6 weeks). During this period the amputation group was trained for two hours daily.

The training programme followed a gradual transition from erect standing, weight-shifting and stepping between parallel bars, followed by walking on regular surfaces with two crutches or sticks, to walking on irregular surfaces without aids. In the latter stages, balance and ambulation were also trained while the patient was performing a secondary visuo-motor task such as throwing and catching a ball. Therapists provided verbal instructions and manual corrections, but no artificial sensory feedback was employed.

All the decisions on the rehabilitation of individual subjects were made independently of the research team. In order to determine whether substantial functional progress had been made, the activity level of every patient was assessed at the end of rehabilitation by means of an amputee activity list (2). The items concerned wearing and handling a prosthesis, indoor and outdoor ambulation and wheelchair use, walking aids, stair climbing, employment and household activities.

Data analysis

Three types of parameters were derived from the CP fluctuations under both feet together (overall CP) in the fore-aft (FA) and lateral (LAT) directions: the mean CP position (Pcp), the root mean square (RMS) amplitude of the CP displacements (Acp) and, after a first-order differentiation, the RMS of the CP velocities (Vcp).

Because the Vcp integrates amplitude and frequency into a single measure of regulatory activity, this measure was primarily used to detect differences in control efficiency between the conditions. It has been demonstrated that parameters related to the average CP velocity show acceptable reliability as well as discriminating power between different physiological and pathological conditions (3, 5, 13, 15, 23, 31). The Acp was regarded as an additional measure of postural sway. Furthermore, the ratio between the Vcp and Acp served to estimate the mean frequency (Fcp) using the following approximation: $\mathrm{Fcp} = \mathrm{Vcp}/(\mathrm{Acp} \times 4 \times \sqrt{2})$ (13).

The Pcp was expressed as a percentage of the maximum length (FA direction) and the maximum width (LAT direction) of support with the zero point at the rear in the sagittal midline (see Fig. 1 A). The base-of-support measures were determined by drawing the circumference of the feet on a piece of paper while the subjects stood on the force platform.

The Vcp was also calculated in two directions under each individual foot. First, the frame of reference was digitally

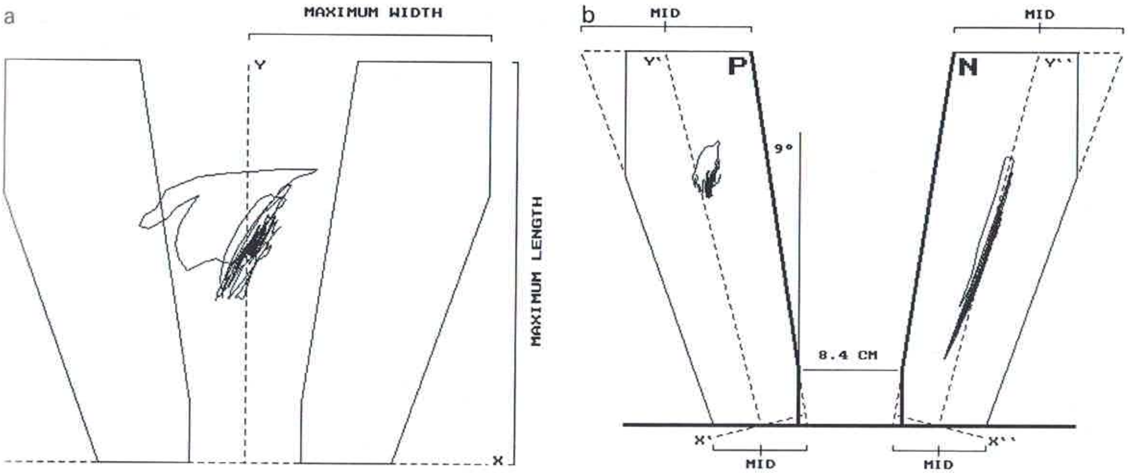

Fig. 1. (*a*) The trajectory of the overall CP is shown for one of the amputees standing with the eyes closed at the start of rehabilitation; the uninterrupted lines indicate the position of the feet; the dashed lines *X* and *Y* refer to the LAT and FA directions of the body frame of reference, respectively. (*b*) The trajectory of the CP under each individual foot is shown for the same registration; the dashed lines *X'* and *Y'*/*X''* and *Y''* refer to the LAT and FA directions of the frames of reference for the prosthetic (P) and normal (N) foot, respectively; the bold lines show the position of the foot frame.

translated and rotated towards the anatomical position of each foot to be able to reliably compare the FA and LAT CP fluctuations under the prosthesis to those under the non-amputated limb. The method which was applied to estimate the longitudinal axis through each foot (FA) from the base of support, and the line perpendicular to this axis (LAT), is visualized in Fig. 1 B.

For each assessment, the comparable results on the two test procedures were averaged into a single score. Thus, three groups of data were obtained—the results of the amputation group at the start of rehabilitation, the results of the amputation group at the end of rehabilitation and the results of the control group.

Statistical analysis

Differences among groups or between conditions within each group were analysed by means of a distribution-free Wilcoxon matched-pairs signed-ranks test.

RESULTS

All the subjects with an amputation had achieved an acceptable level of independent ambulation at the end of rehabilitation. Nonetheless, two patients were excluded from further analysis because of confounding factors. One patient with a (vascular) through-knee amputation developed progressive vascular deficiency of the non-amputated foot. A second patient with a (vascular) above-knee amputation kept falling at unexpected moments during his rehabilitation, which was probably related to mild hemiparesis of the amputated side.

Consequently, the data from eight patients were analysed statistically and compared to the matched control data. The activity assessment showed that four patients had reached "average", two patients "high" and two patients "restricted" activity levels at the end of rehabilitation. As a consequence of the criteria applied in the activity assessment, all the patients were "inactive" at the start of rehabilitation.

Occasionally, a balance test in the absence of visual information had to be interrupted, because the patient came close to falling. In such cases, a second trial was performed. Nevertheless, one patient was unable to stand with blurred vision. Because the blurred-vision condition did not show significant group differences compared to the eyes-closed condition, only the latter condition will be further discussed.

Table I presents the Vcp values of the overall CP for the three groups of data. In comparison with the controls, the persons with an amputation showed less postural control efficiency at all moments in both conditions (FA and LAT sway, $p<0.05$). There was a marked improvement in balance control within the amputation group between the start and the end of rehabilitation assessed by the eyes-closed condition (FA and LAT sway, $p<0.05$). In contrast, the eyes-open condition revealed only a minor improvement in time, which was merely marginally significant on the FA sway (FA sway, $p<0.06$; LAT sway, $p<0.05$). There was a moderate (non-significant) negative cor-

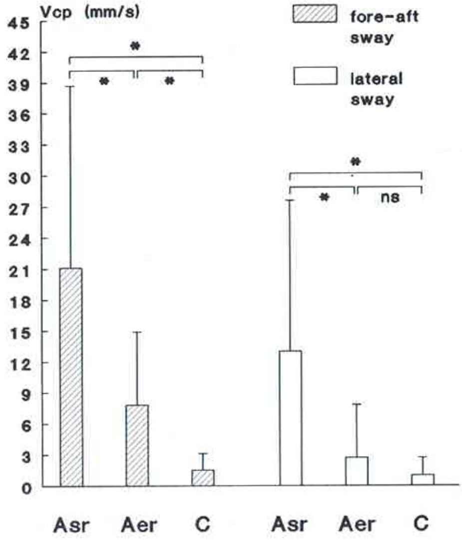

Fig. 2. The group means and SDs of the RMS CP velocity (Vcp) in the eyes-closed minus the eyes-open performance (differential score) are shown for the amputation group at the start (Asr) and at the end (Aer) of rehabilitation and for the control group (C) ($n=8$); $*p<0.05$, ns = not significant (Wilcoxon test).

relation between the activity level and the CP velocity at the end of rehabilitation.

The CP velocity indicated that in every group the FA sway control was less efficient in the eyes-closed than in the eyes-open condition ($p<0.05$). With respect to the LAT sway control, such reduced efficiency in the absence of vision was only significant in the amputation group at the start of rehabilitation ($p<0.05$).

To determine the degree of visual dependency in both planes of balance control, the absolute difference in Vcp between the eyes-closed and eyes-open performance (differential score) was calculated for each test procedure, as well as the relative difference by dividing the eyes-closed by the eyes-open performance (quotient) (23).

The group means and standard deviations of the differential scores are shown in Fig. 2. During the course of rehabilitation, the mean visual dependency for eight persons with an amputation decreased from 21.1 to 7.8 mm/sec on the FA sway ($p<0.05$) and from 13.0 to 2.7 mm/sec on the LAT sway ($p<0.05$). Fig. 3 demonstrates that the same significance was derived from the visual dependency quotients, which decreased from 2.01 to 1.45 on the FA sway ($p<0.05$) and from 2.00 to 1.22 on the LAT sway ($p<0.05$).

In the amputation group at the start of rehabilitation, all the visual dependency scores were greater than in the control group ($p<0.05$). At the end of rehabilitation, only the differential visual dependency scores for FA sway differed significantly from the control values ($p<0.05$).

Relating the Acp to the Vcp values for the three

Table I. *Means and standard deviations of the RMS velocity and amplitude and the mean position of the centre of pressure under both feet (overall CP) in the amputation group and control group ($n=8$)*

Acp = RMS (amplitude) of the CP displacements (mm), Vcp = RMS of the CP velocities (mm/sec), Pcp = mean CP position relative to the base of support (%); in the amputation group positive values in the lateral direction correspond with a deviation towards the normal foot, in the control group towards the right foot

	Amputation group					
	Start rehabilitation		End rehabilitation		Control group	
	Eyes open	Eyes closed	Eyes open	Eyes closed	Eyes open	Eyes closed
Fore-aft						
Vcp	21.4±11.4	42.5±26.8	18.9±11.3	26.7±17.9	7.8±3.0	9.3±3.3
Acp	5.1±1.7	9.8±4.2	4.6±1.6	5.8±2.7	3.8±1.5	4.7±2.1
Pcp	41.9±6.4	42.3±5.9	41.1±5.6	42.5±5.2	41.8±6.3	45.2±6.6
Lateral						
Vcp	12.8±5.6	25.9±18.7	9.8±5.1	12.5±9.9	4.2±1.3	5.2±2.5
Acp	4.8±2.6	6.5±3.4	2.9±0.8	3.8±1.5	2.1±1.0	2.8±1.5
Pcp	9.5±10.4	10.1±8.8	5.4±11.3	7.1±11.1	−6.0±5.7	−6.7±6.3

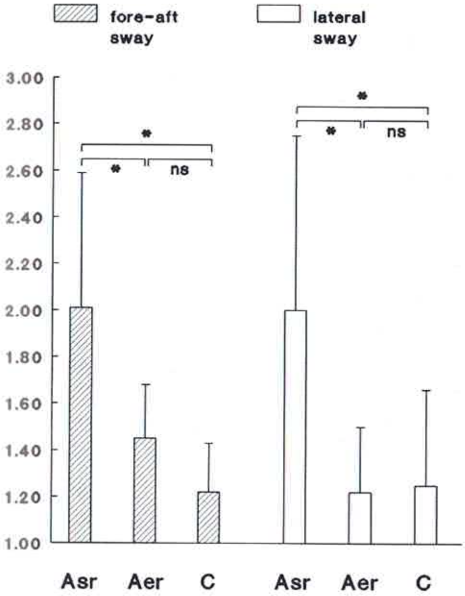

Fig. 3. The group means and SDs of the RMS CP velocity in the eyes-closed divided by the eyes-open performance (quotient) are shown for the amputation group at the start (Asr) and at the end (Aer) of rehabilitation and for the control group (C) ($n=8$); $*p<0.05$, ns = not significant (Wilcoxon test).

groups of data (Table I) revealed that the reduction in postural control efficiency in the absence of vision was largely caused by an increase in Acp in all the groups. Indeed, the mean Fcp in the amputation group remained fairly constant between conditions, varying from 0.6 to 0.7 on the FA sway and from 0.5 to 0.6 on the LAT sway. The control group showed mean Fcp values of between 0.3 and 0.4 in both directions of sway.

Also, the improvement of postural control within the amputation group across rehabilitation was mainly based on a decrease in Acp. Both the FA sway in the eyes-closed condition and the LAT sway in the eyes-open and eyes-closed conditions showed a significant decrease in Acp ($p<0.05$). The decrease in the CP amplitude on the FA sway in the eyes-open condition was not significant.

The Pcp values of the overall CP are also listed in Table I. At the start of rehabilitation, the mean Pcp in the amputation group deviated approximately 10% of the support width towards the normal foot. This deviation corresponded with a mean value of 43% weight bearing onto the prosthesis. At the end of rehabilitation, the mean Pcp was located approximately 6% of the support width towards the normal foot (mean value 45% weight bearing onto the prosthesis). No significant difference in the LAT CP position was found between the start and the end of rehabilitation.

The control group also demonstrated static asymmetry by bearing less weight on the right limb (mean 45%). Static asymmetry in the amputation group was never significantly greater than in the control group. In all groups, the Pcp was within 41% and 46% of the foot length. No significant differences in the FA CP position were found between groups or conditions.

Table II presents the Vcp values under each individual foot for the amputation group before and after the rehabilitation. The control activity in the FA direction was always significantly greater under the nor-

Table II. *Means and standard deviations of the RMS velocity of the centre of pressure under each foot in the amputation group (n=8)*

Vcp-N = RMS of the CP velocities under the normal foot (mm/sec), Vcp-P = RMS of the CP velocities under the prosthesis (mm/sec)

	Start rehabilitation		End rehabilitation	
	Eyes open	Eyes closed	Eyes open	Eyes closed
Fore-aft				
Vcp-N	33.6±22.4	68.1±53.7	30.0±21.7	43.4±34.4
Vcp-P	8.7±2.5	14.2±3.9	8.6±2.7	10.5±3.5
Lateral				
Vcp-N	5.6±2.7	11.7±4.5	3.8±1.7	6.7±4.5
Vcp-P	3.2±1.2	5.6±2.5	2.8±0.8	3.3±1.3

mal than under the prosthetic foot ($p<0.05$). Similar dynamic asymmetry was found with respect to the LAT CP fluctuations under each foot, but was only significant in the eyes-closed condition ($p<0.05$). In contrast, dynamic asymmetry was absent in the control group.

To examine whether the degree of dynamic asymmetry showed any change across rehabilitation, symmetry quotients were calculated. For each test procedure, the Vcp under the normal foot was divided by the Vcp under the prosthetic foot (Vcp-N/Vcp-P) in both the FA and LAT directions. However, this analysis did not reveal any significant decrease in the dynamic asymmetry in either direction.

DISCUSSION

The purpose of this study was to identify relevant motor and sensory determinants of balance restoration following lower limb amputation. Due to the limited number of subjects, the results may not be generalized to all persons with a lower limb amputation. It is, on the other hand, legitimate to lay emphasis on the mutual relations between various characteristics within the same amputation group.

In contrast with some of the earlier studies (4, 6, 7, 11, 32), the amputation group showed less postural control in both directions of sway at all moments. Apart from inter-subject differences, this result can be explained by different instrumentation and parameter choice. Tables I and II indicated that the higher overall-CP velocities in the amputation group were largely caused by higher CP velocities under the normal foot, which means that generally, not the centre of gravity of the body, but the centre of the ground reaction forces as a physical control variable (20, 24) was moving at a relatively high speed.

Furthermore, the high CP velocities in the amputation group were substantially determined by relatively high frequencies. This finding also supported the notion that during stance with the eyes open, there was not so much destabilization as loss of control efficiency in the amputation group. Hence, studies in which the velocity of the centre of gravity was registered (4, 6, 11) or studies which used CP parameters which are less sensitive to frequency (7, 32) may have led to different results.

The activity assessment was primarily meant to determine whether considerable functional progress had been made to presume a general improvement in balance performance. As the items incorporated a broad area of daily activities, some of them completely unrelated to balance (such as putting on and taking off the prosthesis), the lack of a significant correlation between the activity score and body sway was not surprising in such a limited number of subjects.

Visual control of posture was found not only in the amputation group, but also in the control group, at least on the FA sway. Indeed, the influential role of vision in balance control is well-known (14, 26, 27). In accordance with earlier reports (4, 6, 11), an increased dependency on visual information was found to be a marked feature in persons with a lower limb amputation in both directions of sway. This phenomenon can be attributed to a unilateral loss of somatesthesis, in particular from the ankle joint and foot sole. In all the groups, the reduction in postural control efficiency in the absence of visual information coincided with a considerable increase in the CP amplitude, which may reflect a compensatory mechanism to increase the excitation of other input sources (e.g. the vestibulum).

Between the start and the end of rehabilitation, there was much more improvement in balance control assessed with the eyes closed than with the eyes open. The degree of visual dependency in the amputation group, expressed either as an absolute or as a relative measure, showed a major decrease in time in both directions of sway, approaching normal values at the end of rehabilitation. This decrease in visual dependency clearly indicated a central integration of sensory input from the amputated limb into the multisensory control of posture.

This study provided little indication of a symmetrization process following lower limb amputation, either in static or in dynamic terms. Apparently, the amputation group had learned to bear substantial weight on the airboot during the previous phase of rehabilitation. Weight-bearing asymmetry in the amputation group was not significantly greater than in the control group, which was partly due to relatively large inter-subject variability.

In contrast, the amputation group showed significant dynamic asymmetry both at the start and at the end of rehabilitation. It has been shown that a physiological ankle joint and intact lower leg muscles are essential output structures for the utilization of ground reaction forces to maintain equilibrium (12, 22). This study indicated that unilateral damage to these structures causes permanent compensatory control activity of the contralateral limb.

CONCLUSION

Processes which enhance the availability of sensory information from the amputated limb may substantially contribute to balance recovery in persons with a lower limb amputation. This conclusion provides an argument to implement various sensory conditions in the physical training of subjects with lower limb amputation. The ability to process somatosensory information seems to be particularly important in situations of sensory conflict and reduced visual information (21, 23, 25) and may, therefore, be related to the safety of balance performance. This conclusion also has implications for a valid assessment of motor recovery. Unless sensory manipulations are used, afferent aspects of central reorganization processes remain unrecognized in clinical motor assessment. For future research, it seems important to also appreciate such 'hidden' determinants of motor recovery (9).

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