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Biofeedback baropodometry training evaluation: A study with children with equinus foot deformity

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Abstract—The lack of perception in the hindfoot increases the plantar flexion, causing irregular posture due to the foot position, a disability known as equinus foot deformity. A portable device, named baropodometer, that measures the pressure at the forefoot and hindfoot regions was built to help this population in terms of balance and posture correction. Ten hemiparetic teenager volunteers with equinus foot participated in the experiments. The results demonstrated that the proposed device increased the weight-bearing in upright stance in the paretic side, decreasing the weight in the non-paretic side. After 10 experimental sessions, performed along 6 months, the distribution of the pressure in the lower limbs was very similar. The baropodometer facilitates the rehabilitation, by biofeedbacking the pressure of the calcaneus, using the volunteer's audiovisual system. The rehabilitation using the proposed device was able to recover the balance by posture correction, facilitating future gait training of these volunteers.

I. INTRODUCTION

Eighty percent of individuals with neurological disorders have problems in regard to the motor system, affecting their daily routines, and eventually reflecting on social isolation. The majority of these neurological motor disorders are related with endocrine and vascular systems (1).

The physiological muscle changes may impair the speed of motion due to the lack of synchronization among the ankle muscles. Such lack of synchronization can lead to an increase in the stiffness of the muscles, leading to involuntary movements, also called muscle spasticity (2, 3, 4). The lack of synchronization between the ankle extensors and flexor muscles shifts the body weight towards the foot toes, disrupting the heel support and stance phase during walking. Any changes in the normal pattern of the stance position movement produce a reflex that shifts the body weight towards the anterior region of the foot. This behavior of using only the toes, instead of the heels, is known as equinus foot deformity, and probably causes joint deformities. Physiotherapy may be used to improve the distribution of weight, balance, and to avoid social and marketplace isolation (5).

Motor training for static pattern of the gait aids in rehabilitation by decreasing unbalance and falls. Additionally, it might increase independence and self-esteem (6,7). To help with the physical therapy process, a portable device named a baropodometer was built, measuring the pressure at the forefoot and hindfoot regions of both feet.

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In this paper, the results obtained with ten teenagers diagnosed with equinus foot are presented. The excellent results obtained indicate that the proposed methodology helps to improve body balance and future gait training.

II. METHODS

A. Subjects

Ten hemiplegic teenagers, aged between 10 and 18, with equinus foot deformity were invited. The experimental protocol was approved by a local ethic committee. All volunteers were informed and instructed about the participation in the study and parents were asked to sign the 'free and informed consent form'.

B. Baropodometer device

Figure 1(a) shows a simplified sketch of the Baropodometer. It has three major parts, in which labels (A) and (B) are the four displays and the bar graphs showing the pressure applied in the piezoresistive pressure sensors (E-H), respectively. Figure 1(b) shows a picture of the piezoresistive sensors placed over a rigid rubber. The rigid rubber was cut and used to replace the insole of a sandal. The piezoresistive sensors are fixed in the insoles and connected to an electronic device by a pair of flexible wires (D).

The interface shows four bar graphs made with LEDs, label (B), which indicates the pressure on each sensor, labels (E-H). The sensors are placed at the distal and the other one in the proximal regions of the foot. Each sensor can measure pressure variation up to 50 kgf/cm2. The four potentiometers, label (C), are used to adjust the pressure range according to the each volunteer's weight. A sound circuit to produce a continuous sound with frequency proportional to the weight placed on the sensors was also implemented,. Another potentiometer is used to adjust the frequency range.

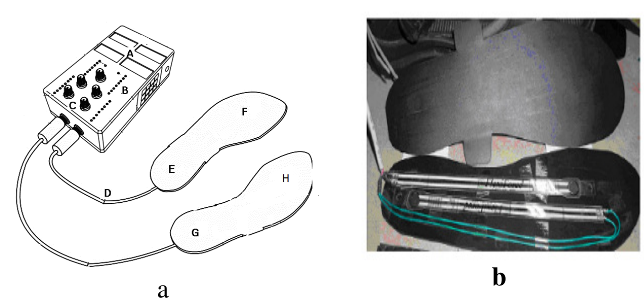


Figure 1. Baropodometer Device: (a) Sketch of its main parts, where labels (A) and (B) indicate the 4 displays and bar graphs LEDs that indicate the readings in the piezoresistive pressure sensors (E to H); C are

the potentiometers used to adjust the end scale sensibility and the output frequency range; (D) flexible wires that connect the sensors to the device. (b) Picture showing the piezoresistive sensors location in the rigid rubber insole.

C. Stabilometry

All volunteers were submitted to a stabilometric study using a F-Scan-TEKSCAN® equipment, in order to register the weight distribution in the foot sole. This equipment has a rectangular sensor plate, with size 46 cm by 35 cm. The stabilometric studies were conducted eight days before and after the experiments sections with the baropodometry. In this way, it was possible to evaluate if there was a motor learning, i. e., if the volunteer increased the weight-bearing in the affected heel (the heel without sensibility). Before the stabilometric study, all volunteers received orientation about the experiment´s procedure in order to learn how it works, its application, and how the experiment was developed.

The subjects were positioned on the stabilometer in an upright posture, keeping their feet in parallel position, and separated by 15 cm of distance. The volunteers were oriented to keep their arms along the body and also to attempt to apply weight on both heels.

D. Training

The subjects were asked to wear a pair of sandals and to stand up, trying to keep themselves in the upright position with their feet in parallel. For this training, the subject kept looking at the interface and tries to maintain all the bar graph with the same number of LEDs on. Next, the equinus foot is moved until the rear line of the calcaneus is aligned with the toe line of the other (unaffected) foot. The volunteers are then instructed to lean the body towards the side of the equinus foot, in a way to provide pressure to the affected foot. This small inclination of the body, with the equinus foot aligned ahead, increases the pressure´s distribution around the entire foot sole, rather than only at the foot ´s heel.

At this stage, the pressures in the forefoot and hindfoot of the equinus foot were registered for the period of sixty seconds. The maximum pressure, reached at this period in the calcaneus, was defined as the target pressure. This target pressure is defined as the pressure aim to be reached in the next session.

Then, the volunteer is asked to bring the equinus foot back, Fig. 2(b) until both feet are aligned again. However, at this time he tries to keep the pressure on the heel. Since the subject does not have the feeling of pressure in the heel, he uses the LEDs of the bar graphs, as a reference for checking the pressure that he is applying. This procedure is repeated fifteen times in each experimental session of twenty minutes.

At the end of each session, with the feet in parallel and in the upright stance position, the sensors' pressure of the equine foot is registered for sixty seconds. In this way, it is possible to compare de maximum values of pressure in the calcaneus, before and after each session.

III. RESULTS

Fig. 2 displays images of a 14-year-old volunteer, who has equinus foot in his left foot and using the baropodometer. In this experiment, a counter desk was used by the volunteer to help him to maintain his balance. The baropodometer was placed over the counter near to the volunteer's eyes to make it easier for the subject to see the changes at the bar graph and displays. The volunteer was oriented to slide his left foot ahead, without raising it, and keeping the pressure in his calcaneus (Fig. 2(a)). Next, during the foot sliding backward, the volunteer kept looking at the bar graph and displays of the baropodometer, as a reference for the pressure that he was applying on his calcaneus.

Fig. 2(b) shows the volunteer at the end of the training session with both feet in parallel, standing in another position. In this position the aim is to maintain the lower limbs aligned avoiding the rotation of his hip and keeping the upright posture.

(a) (b)

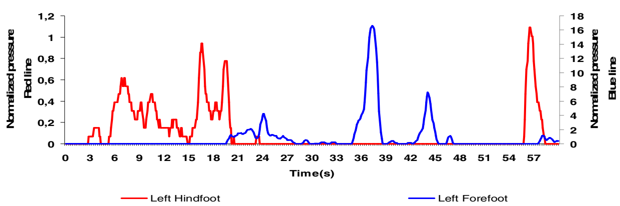
Figure 2. Pictures of a volunteer using the baropodometer device: (a) Initial stage - He slides back his paretic foot, trying to keep a constant pressure in the calcaneus region using the baropodometer; (b) Final Stage - with his feet aligned and keeping the calcaneus pressure in an upright posture.

In Fig. 3 it is shows 60 seconds of the pressure variation in the forefoot (blue line) and hindfoot (red line) regions of the affected (left) foot. The pressure signal was acquired at the beginning of the training session, with the paretic foot placed ahead. In Fig. 3(a), between 3 s and 20 s the subject is trying to keep the pressure in the calcaneus. In the period from 21 s to 47 s, there is a cutaneous tonic reflex in the left calf, bringing all the pressure to the forefoot (8, 9, 10). Also, from 47 s to 55 s, the volunteer transferred all the weight to the non-paretic side. In the last 5 s, the volunteer returns the weight to the left leg. On the other hand, Fig. 3(b) shows the 60 s of pressure variation at the end of the same training session, where both feet are placed in parallel. It is possible to observe that during this period the volunteer kept some pressure in the hindfoot. Also, co-contraction can be observed at the tibialis anterior muscle since there is no pressure in the forefoot.

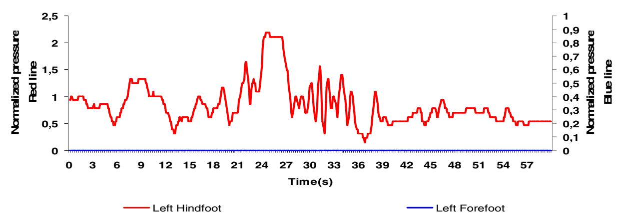
In Table 1, the maximum normalized pressure values registered are presented at the end of the ten sessions. For each of the ten volunteers (V1, V2…V10), the maximum pressure value of these ten sessions was used to normalize the measured pressures.

A. Center of pressure variation

Fig 4 shows the results of one of the stabilometric studies (14-year-old volunteer with the equines right foot), showing the pressure´s distribution in two different moments: performed eight days before the beginning of the training sessions, Fig. 4(a), and eight days after the ending Fig. 4(b). In this figure, it is noticeable that most of the body weight is displaced to the left foot. Also, comparing the left and the right foot at the stabiliometic study, there is a clear indication that almost no weight is being applied in the right foot, especially in the calcaneus. The center of pressure (COP) is indicated with a small icon at the center of the figures. In Fig 4(a) the COP is shifted to the left side, indicating that before the experiments the volunteer was applying more pressure in the left foot, rather than distributing the weight more evenly between the feet, Fig. 4(b).



(a)



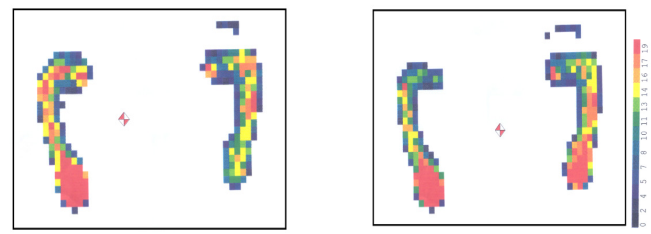
(b)

Figure 3. Graphs showing the registered pressure signals in the left foot sensors, placed in the forefoot and hindfoot. These signals were registered in the 4th (among all the 10 training sections): (a) Beginning and (b) end of the training session.

TABLE I. SHOWS THE NORMALIZED PERCENTAGE OF THE PRESSURE VALUES IN THE HINDFOOT REGION OF THE TEN VOLUNTEERS (V1-V10) AT THE END OF THE TENTH TRAINING SESSIONS.

Training Sessions	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10
1	7	20	15	0	0	16	24	28	28	5
2	1	5	1	1	33	4	11	18	36	41
3	7	88	20	13	14	1	18	9	30	48
4	6	100	3	2	6	18	16	6	11	25
5	7	59	6	27	6	42	32	14	44	54
6	42	88	7	32	6	11	23	31	35	23
7	26	54	12	75	11	78	33	36	73	25
8	49	85	53	62	27	10	64	51	45	85
9	62	93	37	100	49	94	66	100	85	82
10	100	92	100	80	100	100	100	79	100	100

Fig. 5 shows the displacement, represented in percentage of the COP, before the beginning of the training (blue bars) and after the end of the training (red bars) with the baropodometer. Positive and negative values indicate the COP shifted to the right and left sides, respectively. Volunteers V1, V5, V6 and V9 have paresis in the left side. It is possible to observe that from these ten volunteers there is no correlation between the hemi-paretic side and the COP.



(a) (b)

Figure 4. Stabilometric study of the pressure distribution in the feet´s sole of a 14-year-old volunteer with the equinus right foot. (a) Eight days before the beginning of the training. (b) Eight days after the end of the last training session. The icon in the center of each figure indicates de Pressure Center. The color scale is in kgf/cm².

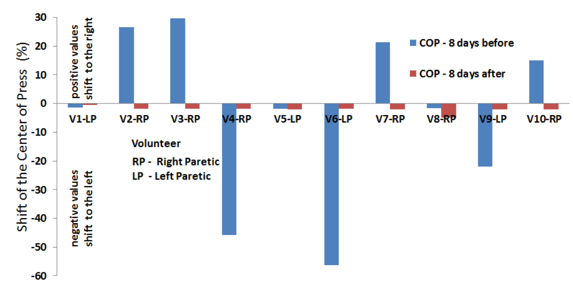


Figure 5. Result of the stabilometric study performed with ten volunteers.

Fig. 6 shows the average of the normalized percentage of the pressure values in the hindfoot region in the ten sessions (Table 1). Most of the volunteers are winthin 30 and 50% of the maximum weight in the paretic heel, except volunteer V2, that reach reached 70% of the weight in the paretic heel.

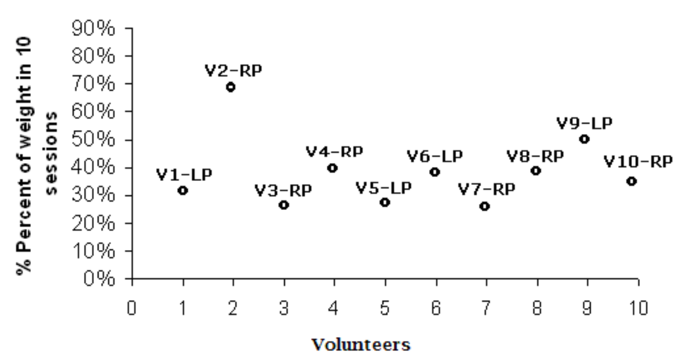


Figure 6. Average of the normalized percentage of the pressure values in the hindfoot region in the ten sessions.

IV. DISCUSSION

The graphs in Fig. 3 indicate that after ten training sessions, the volunteers were able to increase the pressure in the calcaneus of the equinus foot. Thus, the rehabilitation by biofeedbacking the calcaneus pressure through the visual system, promotes the sensory-motor stimulation of the muscle in the ankle, reducing the equines foot position in gait (11).

Table 1 shows the maximum pressure applied in the hindfoot region of the ten volunteers, registered at the end of each one of the ten training sessions.

It can be observed that in the first sessions, most of the volunteers were not conscious about de calcaneus pressure of the equinus foot (values < 20%). However, at the end of the 10th session, 70% of them reached its maximum weight capacity. The other three volunteers (V2, V4, and V9) reached the maximum pressure before the last session. This may result for various reasons, such as: lack of perception of the calcaneus, difficulties in the motor learning process, lack of personal interest, among others. Therefore, with the baropodometer device it is possible to help postural training, neurophysiological responses, tonus control, and to correct sequelaes and deformations (12).

Fig. 6 shows an average of the weight applied in the heels at the end of each experimental session. Most of the volunteers were capable to maintain a certain amount of weight in the paretic heel that was above the pressure applied before the training period. It means that they have memorized the mechanical work that was carried out in the session. At the end of the experiments, 7 volunteers reached their highest capacity of pressure in the paretic heel.

The stabilometric study and static training enable us to verify that the perception of the calcaneus pressure was increased. Also a more even distribution of the weight between both feet was observed, as well as the fact that the pressure center moved to the center of gravity.

V. CONCLUSION

In this paper, ten teenagers with equinus foot syndrome took part on an experimental study with a baropodometer device, specially developed for motor skills' rehabilitation. The aim of the baropodometry is to facilitate the rehabilitation by biofeedbacking the pressure of the calcaneus, using the volunteer´s audiovisual system. The rehabilitation using such device was able to recover the unbalance and the lack of equal distribution between the feet of these volunteers.

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