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# Similarities and Differences in Manual Stretching of Physical Therapists for Equinovarus

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***Abstract*— For equinovarus, a foot condition commonly suffered as a side effect of stroke, sustained muscle stretching is the primary form of treatment, most of which is manually performed by physical therapists (PTs). It is important to identify variations in the execution of manual stretching techniques by PTs for the standardization of therapeutic techniques. In this study, manual stretching motions performed by three PTs on one stroke survivor were analyzed in terms of foot posture and the force and torque applied to the diseased foot, which were measured through a motion capture system and instrumented foot brace. Statistical analyses based on the principal component analysis showed that many of the stretching motions of the PTs were similar in that they served to control the deformed foot. However, individual differences were observed in the force applied to the heel and the inversion and eversion torque around the ankle, suggesting that individual PTs may stretch different muscle groups. Furthermore, there are potential differences in the efficiency of stretching technique execution among PTs.**

Fig. 1. Equinovarus. Right foot: deformed. Left foot: healthy.

## I. INTRODUCTION

Equinovarus is one of the major side effects developed in the foot on the paralyzed side of the body of stroke survivors. Owing to this symptom, the plantar flexors of the foot become overly excited, and human postural control is impaired during standing and walking [1], [2]. As shown in Fig. 1, unintended plantar flexion and inversion of the foot result. The gait stability decreases because of the marginal contact between the ground and the deformed sole [3]. An epidemic study reported that approximately 30% of stroke survivors have a foot deformity [4]. These issues typically continue after discharge and diminish the ability to perform daily activities and the quality of life [5].

For equinovarus, common treatment is stretching of the spastic muscles of the foot. Sustained stretching prevents the chronic shortening and hyperexcitation of these muscles and maintains a healthy range of joint motion [6], [7], [8]. Some variations exist in the clinical stretching for equinovarus foot. Some studies compared the effects of static and cyclic stretching, and others discussed whether or not the torque applied to the foot during stretching should be constant [7], [9]. According to these studies, both static and cyclic stretching were effective for decreasing joint stiffness. However, static stretching led to greater relaxation of deformed foot torques than cyclic stretching did. Whereas some have studied effective stretching techniques for equinovarus regarding the strength and duration of stretching, thus far, few studies have focused on the complexity of the foot joint. There have rarely been studies on the directions of torques applied to the foot and their time course during stretching. The purpose of stretching is to stretch muscles and tendons running through a three-dimensional body structure. In particular, the ankle consists of multiple degrees of freedom in motion and several related muscles. Hence, the direction of stretching is very important, and so are its strength and duration.

In clinical rehabilitation, a large part of stretching treatments for equinovarus is manually performed by physical therapists. They typically stretch the spastic or shortened muscles of the foot in its dorsal direction by applying a sufficiently strong force on the foot sole. They must be sure to maintain control of foot during inversion/eversion and adduction/abduction motions. Because motions of the ankle around its multiple axes affect each other, directions and timings of forces, which are applied to the foot by therapists, depend on and are regulated by the muscles related to equinovarus. Furthermore, in order to smooth the movement of the ankle joint during stretching, some therapists pull the heel of the subject and decrease the pressures between bones in the ankle joint. Despite their complexity, the techniques of stretching are not quantitatively described, and physical therapists learn them experimentally. Hence, the effectiveness of manual stretching motions for equinovarus often relies on the execution of individual therapists, and there are potential differences in the execution of stretching techniques among therapists.

In this study, the kinematic and force properties of manual

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stretching motions for treatment of the equinovarus foot of a stroke survivor were investigated, and the similarities and differences in execution among the therapists were identified. The patient wore an instrumented brace on his diseased foot, which was developed for this study, through which each therapist stretched the related muscles. The results of this study are helpful for identifying individual differences in stretching techniques for equinovarus and contributing to their standardization.

## II. EXPERIMENT

This study was approved by the Institutional Review Board of Graduate School of Engineering, Nagoya University.

### A. Subjects

Three male PTs with at least three years of experience in rehabilitation for stroke survivors and one male stroke survivor at Brunnstrom Recovery Stage IV were invited to participate in this experiment. The experimental procedures and purposes were explained in both written and verbal form to the participants, and all of them signed a written informed consent agreement.

### B. Measurement method and experimental system

The main part of the experimental apparatus was an instrumented shoe brace through which PTs stretched the patient's ankle, as shown in Fig. 2. Generally, in order to stretch the ankle plantar flexors, PTs push the plantar surface using their forearms while gripping the heel of the patient. Hence, forces applied to both the forefoot and heel were measured by installing three- and six-axial force sensors on the forefoot and heel of the shoe brace, respectively. The shoe brace was fastened to the patient's foot using fabric bands, and the gaps between the foot and brace were filled with rubber plates and sponges to tightly fix them while avoiding possible pain. This tightening allowed the therapists to apply sufficient forces to the brace as they clinically do for the bare foot of patient.

A three-dimensional motion capture system (VENUS3D, Nobby Tech. Ltd., Japan) was used for measuring the stretching motion, which also allowed for synchronization of the force sensors and cameras. The system recorded the positions of reflective markers attached to the patient's thigh and brace at the rate of 120 Hz.

### C. Experimental task

The patient wore the shoe brace on his left paralyzed foot and lay relaxed on a bed. Each PT stretched the patient's foot through the brace. The PTs were instructed to perform the stretching as they did in a clinical setting. One trial of stretching lasted ten seconds, and in a single set of the experiment, three trials were repeated with a rest period of five seconds between trials. In total, three sets were conducted for each therapists, with a one-minute break after each set.

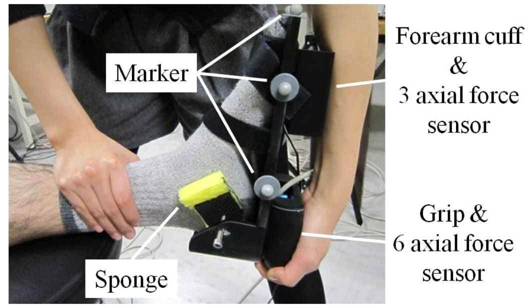


Fig. 2. Foot brace with two force sensors. A patient wore the brace on his diseased foot through a sock. A PT held the heel grip and placed his/her forearm against the forearm cuff.

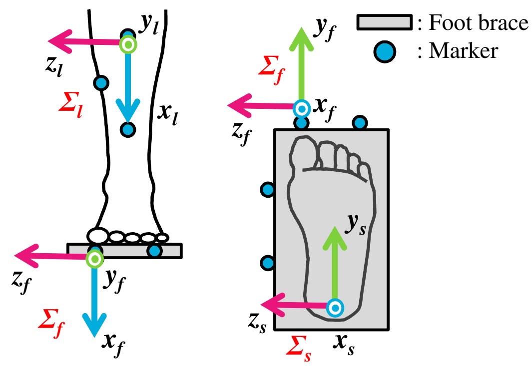


Fig. 3. Coordinate systems ($\Sigma_l$, $\Sigma_f$, and $\Sigma_s$)

### D. Coordinate systems

Seven reflective markers were used for the motion capture system. Two markers were placed on the anterior border of the patient's tibia shin bone. One marker was also attached on the bone's medial surface. The shoe brace had four markers attached, as shown in Fig. 3. Two of them were located on the frontal part, and the other two markers were on the medial part of the brace.

Using these markers, two coordinate systems were defined: lower leg ($\Sigma_l$) and foot ($\Sigma_f$), as shown in Fig. 3. The origin of the lower leg system was set to the position of the proximal marker among those attached on the anterior border of the tibia bone. The direction of the X axis ($\boldsymbol{x}_l$) was set along the anterior border of the tibia bone. $\boldsymbol{z}_l$ and $\boldsymbol{y}_l$ were defined along and orthogonal to the frontal plane, respectively, based on the markers on the tibia bone. The foot's coordinate system was defined such that its basic axes were parallel to those of $\Sigma_l$ in the basic human standing posture. $\boldsymbol{x}_f$ was defined as perpendicular to the plantar surface, and $\boldsymbol{y}_f$ was along the longitudinal direction of the brace. The origin of the foot system was placed on the frontal medial marker of the shoe brace. Furthermore, the coordinate system of the six-axial force sensor ($\Sigma_s$) was fixed on the sensor's position and along the posture of $\Sigma_f$.

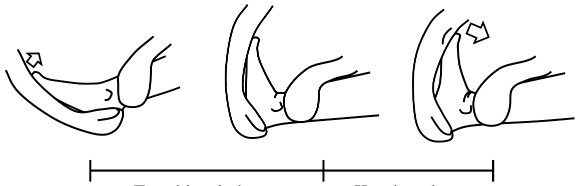


Fig. 4. Two phases of stretching. In the transitional phase, the deformed foot is placed in the flexed posture. In the keeping phase, the ankle flexors are stretched with strong forces.

### *E. Data analysis*

*1) Three types of data to be analyzed:* In the analysis, the following three types of data were used: foot posture, foot force, and torques applied to the foot brace.

The foot posture was defined as the roll-pitch-yaw angles between the lower leg and foot coordinate systems. For this end, we computed the rotation matrix ${}^{l}\boldsymbol{R}_f$ between the two coordinate systems, and decomposed it into roll, pitch, and yaw angles. This process is described as follows:

$$ {}^{l}\boldsymbol{R}_f = [{}^{l}\boldsymbol{x}_f \; {}^{l}\boldsymbol{y}_f \; {}^{l}\boldsymbol{z}_f] = \boldsymbol{R}_z({}^{l}\theta_z)\boldsymbol{R}_y({}^{l}\theta_y)\boldsymbol{R}_x({}^{l}\theta_x), \quad (1) $$

where ${}^{l}\theta_x$, ${}^{l}\theta_y$, and ${}^{l}\theta_z$ are the roll, pitch, and yaw angles, respectively, of the foot from the viewpoint of the tibia coordinate system.

The six-axial torque sensor on the heel output three force components (${}^{f}\boldsymbol{f}_x$, ${}^{f}\boldsymbol{f}_y$, ${}^{f}\boldsymbol{f}_z$) and moments (${}^{f}\boldsymbol{m}_x$, ${}^{f}\boldsymbol{m}_y$, ${}^{f}\boldsymbol{m}_z$). As described before, these force and torque values were expressed from the viewpoint of the foot coordinate system.

Note that it was not possible to acquire the outputs from another force sensor on the forefoot owing to a problem of electronic circuits; therefore, data from the forefoot sensor was not used in the analysis.

*2) Segmentation of stretching into two phases:* As shown in Fig. 4, a single foot stretching was split into two phases: transitional and keeping. The transitional phase spans from the beginning of the stretching to the point at which the foot was dorsiflexed. The keeping phase is the period during which the muscles and tendons affected by equinovarus were continuously stretched with relatively large manual forces. A border between these two phases was defined using the acceleration of the dorsi/plantarflexion angle of the foot. When this angular acceleration reached its minimum value, the transition phase ended and the keeping phase started. The focus of this study was on the transitional phase in the latter analysis.

*3) Principal component analysis of motion and force data:* The time-sequential data was downsampled to the length of 100 because individual PTs performed foot stretching at their own preferential paces, so each stretching differed in duration. The downsampling was conducted according to

$$ x_d[i] = x_r[i \times \Delta] \quad s.t. \; \Delta = \frac{\text{length}(x_r)}{100}, \; i = 1, \ldots, 100, \quad (2) $$

where $x_r$ was for the data before the downsampling and $x_d$ was for after. We applied a principal component analysis on the downsampled data. To analyze the time-sequential and multidimensional data, an extended vector composed of the following nine variables was prepared: ${}^{l}\theta_x$, ${}^{l}\theta_y$, ${}^{l}\theta_z$, ${}^{f}f_x$, ${}^{f}f_y$, ${}^{f}f_z$, ${}^{f}m_x$, ${}^{f}m_y$, and ${}^{f}m_z$. Each of these variables had standardized one hundred values. Hence, the extended vector was defined as $\boldsymbol{v} = ({}^{l}\boldsymbol{\theta}_x^T \; {}^{l}\boldsymbol{\theta}_y^T \; {}^{l}\boldsymbol{\theta}_z^T \; {}^{f}\boldsymbol{f}_x^T \; {}^{f}\boldsymbol{f}_y^T \; {}^{f}\boldsymbol{f}_z^T \; {}^{f}\boldsymbol{m}_x^T \; {}^{f}\boldsymbol{m}_y^T \; {}^{f}\boldsymbol{m}_z^T)^T$, which had a length of 900. This extended vector was used for each stretching. Since twenty-five valid trials of stretching were acquired, with two out of twenty-seven trials being considered invalid, the data matrix ($\boldsymbol{D}$) of all stretching became 900 $\times$ 25 in size. A principal component analysis was applied on $\boldsymbol{D}$.

## III. RESULT

Valid data obtained in this experiment were the forces and moments measured using the six-axial force sensor and the coordinates of the seven reflective markers attached to the lower leg of the patient and the shoe brace. Therefore, these data were analyzed in the transitional phase.

### *A. Sample of stretching-related posture, force, and torque*

As an example, the averages of foot position, force, and moment from one PT are shown in Fig. 5. These are the results of the dynamics between the foot of the patient and the therapist. In terms of the foot posture, the main motions were dorsiflexion (around the Z axis) and abduction (around the X axis). There was little deformation of inversion/eversion in the patient's foot. For this PT, the forces were applied along all three directions, and their absolute values increased as the 100% mark of the cycle was approached. As for the moment, the dorsiflexion moment (around the Z axis) was remarkable, whereas the other components were relatively minor. The change in the Z moment was as much as 700 mN·m, while those in the X and Y moments were approximately 200 mN·m at most.

### *B. Results of principal component analysis*

From the principal component analysis, two principal components were acquired, with the contribution ratios of each component being 64.0% and 22.0%. Fig. 6 shows the primary and secondary components for the foot posture, force, and torque. Note that all variables appear equally significant in terms of magnitudes; however, this is because they were standardized before the analyses.

*1) Principal components of foot posture (roll-pitch-yaw angles):* As described above, the foot posture mainly varied around the Z axis (dorsi/plantar flexion) and the X axis (ad/abduction), whereas its change around the Y axis (e/inversion) was minuscule. As shown in Fig. 6 (top), the primary and secondary components of the foot posture were largely similar to each other in terms of their profiles. This suggests that the profiles of the foot posture did not vary significantly among the trials and PTs. The angle around the Z axis gradually increased in both the primary and secondary components, indicating that the foot was monotonically flexed to the dorsal direction. Also, the foot was continuously abducted because the angle around the X axis constantly decreased during the entire stretching phase.

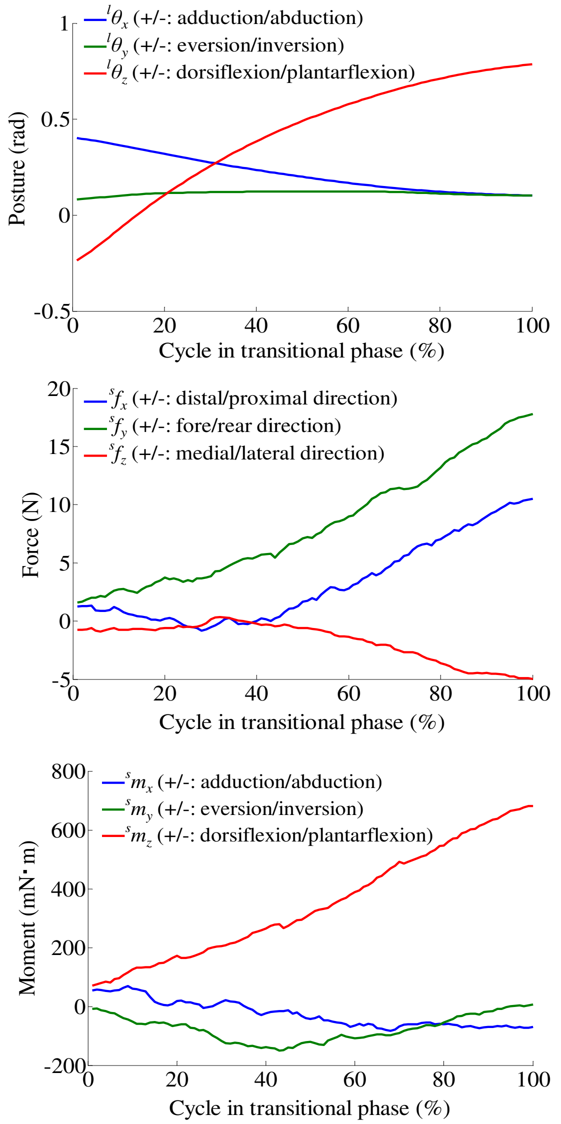


Fig. 5. Average torques and forces applied to the foot and its posture during the stretching performed by one PT. Top: posture. Middle: force. Bottom: moment. Posture and moment: X (+/-: adduction/abduction), Y (+/-: eversion/inversion), Z (+/-: dorsiflexion/plantarflexion). Force: X (+/-: distal/proximal direction), Y (+/-: fore/rear direction), Z (+/-: medial/lateral direction).

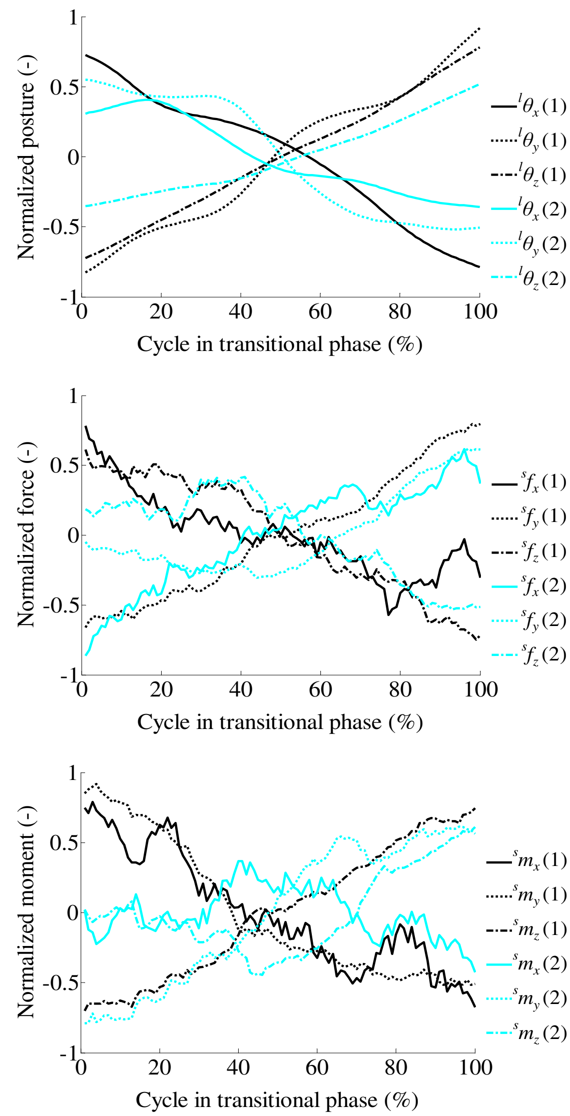


Fig. 6. Results of principal component analysis. $x(1)$, $y(1)$, and $z(1)$ are the primary components, and $x(2)$, $y(2)$, and $z(2)$ are the secondary components.

*2) Principal components of force applied to rear foot:* As shown in Fig. 6 (middle), for the force along the X axis, the first principal component decreased continuously, whereas its secondary component increased. This indicates that the heel was pushed in some trials, but pulled in the other trials during stretching. In terms of the force along the Y axis, the first principal component increased constantly, whereas the second component started to increase in the last part of the cycle. The trials differed in terms of when the Y-axis forces started changing. For the Z-axis force, the first component decreased continuously. On the other hand, the second component began to decrease at 40-50% of the cycle. There might have been a variation in the onsets of the Z-axis forces among the trials.

*3) Principal components of moment around rear foot:* As described before, the changes in the moments around the X (ab/adduction) and Y (e/inversion) axes were somewhat minor, but the profiles of the Y-axial moments were very different in the primary and secondary components. As shown in Fig. 6 (bottom), its primary component continuously decreased, whereas its secondary component behaved oppositely, indicating that substantial differences in Y-axial moments existed among the trials, the PTs, or both.

The moment around the Z axis (dorsi/plantarflexion) was larger than the moments around the other two axes in Fig. 5 (bottom). Its first component increased significantly, whereas its secondary component started increasing at approximately 40% of the cycle. This suggests that the dorsiflexion moment varied among the trials or PTs in terms of how it increased, but it basically increased for all of the trials.

## IV. Discussion on individual differences in stretching

The results of the principal component analysis of the stretching showed similarities and differences in the execution of stretching techniques among the therapists. According to the primary component of forces (Fig. 6 middle), which represents the general trends of stretching, PTs gradually increased their forces on the heel grip to the toe side ($+Y$) and lateral direction ($-Z$). Also, as shown in the bottom panel of Fig. 6, the ankle was continuously dorsiflexed (around $+Z$). These are consistent with the changes in the foot posture shown in Fig. 6 (top), indicating that the foot was primarily abducted and dorsiflexed during the transition phase. Since equinovarus causes hypertonia in the ankle flexors and plantar flexion, inversion, and adduction of the foot, it is reasonable to assert that the PTs provided stretching such that these foot deformations were alleviated.

In contrast, the secondary component represents the difference among PTs or trials. Notably, the X-axis component of the force applied to the heel showed clearly distinguished trends. Its secondary component monotonically increased, whereas its primary component monotonically decreased. Such a difference in the principal components clearly appears in the average values of the X-axial force of each PT (Fig. 7). PT1 and PT3 applied the X-axis force in the positive direction, indicating that they pulled the heel. In contrast, the X-axis force of PT2 was negative, indicating that he pushed the patient's heel. Therefore, it is presumed that PT2 applied a larger force to the forefoot in order to dorsiflex the ankle joint than the other PTs did, although it was not possible to acquire the force values on the forefoot owing to an electronic problem. Such stretching by PT2 is considered inefficient in terms of energy loss because the forces applied to the heel and forefoot oppose each other.

Furthermore, the profiles of the Y-axial (eversion/inversion) moment significantly differ between the primary and secondary components. Its primary component gradually decreased, whereas its secondary component did the opposite. As shown in Fig. 8, such a difference can be seen in the average Y-axial moments among the three PTs. PT3 apparently applied large eversion torques on the foot. On the other hand, those of PT1 and PT2 were negligible or even inversion torques. This difference in eversion and inversion torques applied to the foot potentially leads to the difference in the groups of muscles being stretched. Whether or not such a difference is important for the stretching against equinovarus remains to be determined in a future study.

In this experiment, since the period of transitional phase varied either among each trial or PTs, the obtained data was downsampled for analysis. Owing to this process, it was not possible to discuss the dynamics of stretching. The analysis of such dynamics is left for a future study, although stretching usually does not involve quick but slow joint movements.

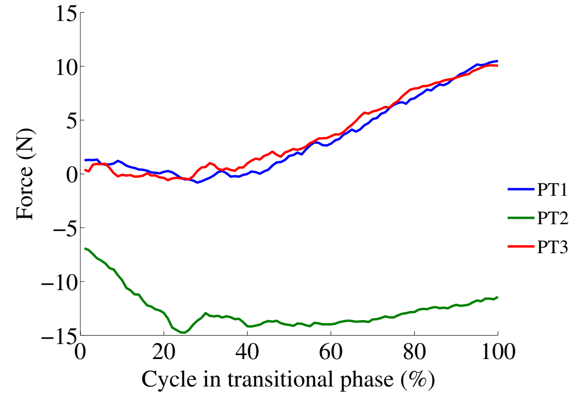


Fig. 7. Average X-axial heel forces for individual PTs.

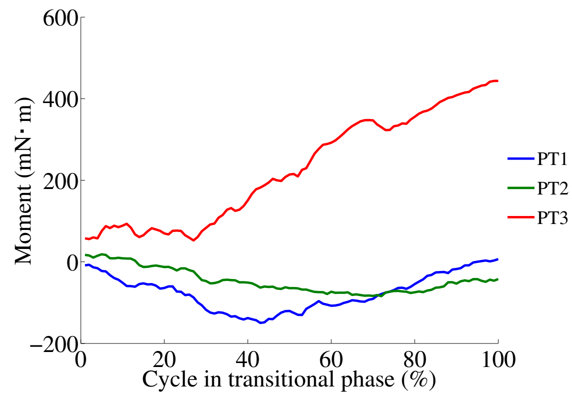


Fig. 8. Average torques around Y axis for individual PTs.

## V. Conclusion

Execution of manual stretching techniques for equinovarus inherently varies among PTs, owing to the musculoskeletal complexity of the human ankle joint. In this study, the performances of manual stretching by PTs for treatment of the equinovarus of a stroke survivor were investigated. PTs stretched the deformed foot of the patient as they usually did in their clinical scenes through an instrumented shoe brace worn on the patient's foot. A motion capture system and multiaxis load cells acquired kinematic and force profiles during stretching. The collected data were processed based on a principal component analysis to identify the similarities and differences of the stretching techniques among the PTs. All PTs commonly transferred the diseased foot such that the symptomatic deformation (plantar flexion and adduction) of the foot was corrected. On the other hand, there were individual differences in the force applied to the heel and the magnitude of the eversion moment. In particular, one PT pushed the heel in the proximal direction, while the other two PTs pulled it during stretch. Furthermore, one PT apparently applied eversion moments to the ankle, whereas the others did not. These differences could potentially be used to define levels of efficiency in stretching technique execution. The next step is to identify an effective stretching technique by revealing how the individual's execution affects the therapeutic outcome. We will study further with sufficient numbers of patients and PTs to acquire statistically valid data.

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