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Original Article

Stability Analysis in Individuals with Complete and Incomplete Spinal cord Injury: Linear Versus Non-Linear Methods

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ABSTRACT

Background: Individuals with spinal cord injury (SCI) lose their abilities to stand. The effectiveness of compensating strategies such as the use of various orthosis is studied by stability analysis. These kind of analyses are usually studied by linear method. In this study, the standing stability of complete and incomplete SCI individuals is evaluated by linear versus non-linear methods.
Methods: Study groups consisted of 10 normal, 5 incomplete and 5 complete SCI individuals. SCI participants stood with crutch and/or orthosis on a Kistler force plate. The excursions of center of pressure (COP), velocity of COP, correlation dimension, and approximate entropy in the anteroposterior and mediolateral planes were calculated in this study. Statistical analysis was done by one-way ANOVA and Post-hoc calculations by Tukey HSD.
Results: Linear method revealed that the difference in "the mediolateral COP sway" and "anteroposterior COP velocity" was insignificant among the groups, whilst the difference in "anteroposterior COP sway", "mediolateral COP velocity" and "total velocity" was significant. In contrast, non-linear method revealed that the difference in "mediolateral embedding diversion", "anteroposterior embedding diversion", "mediolateral correlation dimension" and "anteroposterior ApEn" was insignificant among the groups, whilst the difference in "anteroposterior correlation dimension" and "mediolateral ApEn" was significant.
Conclusion: Based on linear method, the stability of SCI subjects seems to be like normal subjects. However, non-linear analysis revealed that although SCI patients knew how to put their body in a good posture to have a stable position, they had no abilities to control their posture.

Introduction

Spinal cord injury (SCI) is defined as damage to the spinal cord. SCI leads to loss of function, sensation and mobility below the level of injury. It influences the abilities of subjects to stand and walk, depending on the level of injury [1-4]. The annual incidence of this injury varies among countries (i.e. 12.7 new cases per million in France and 59 new cases in the United States of America) [4-7]. The SCI individuals use orthoses and wheelchair to ambulate from one place to another [2]. Various types of orthoses such as Louisiana State University reciprocal gait orthosis (LSU-RGO), advance reciprocal gait orthosis (ARGO), Hip guidance orthosis (HGO), Knee ankle foot orthosis (KAFO) and Mohammad Taghi Karimi reciprocal gait orthosis (MTK-RGO) have been developed to enhance the performance of the subjects during standing and walking [8-16]. However, most of the subjects prefer not to use any orthosis due to high energy demand during walking, too much force applied on upper limb and speed of walking which is significantly less than using wheelchair compared to normal walking [17-20].

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The main reasons for using orthosis for paraplegic subjects include; improving bone mineral density (IBM), decreasing bone osteoporosis, improving the performance of cardiovascular and digestive systems and to reduce joint contracture and muscle spasms [8, 20, 21]. Moreover, most SCI individuals have a willingness to stand and to execute different hand tasks and their daily activities. Most researches about SCI are based on the modeling and/or passive orthosis when the subjects stand for a short period of time [16, 22-30]. They only compared the stability of SCI subjects when using different orthoses, but did not pay attention to their stability problems and the challenge which they may encounter during standing. Baardman et al., Minato et al. and Middleton et al. evaluated the stability of paraplegic subjects when standing on force plate for a short time (between 0.5 to 1 minute) [22, 31, 32]. The stability was evaluated by the use of linear analysis approach (center of pressure (COP) sway excursion, velocity). These kind of studies mainly describe how much the COP move around (quantity of movement) [33, 34], but they do not evaluate how well the movements of COP are (quality of movement) [33]. Nonlinear analysis is another method which has been used in other researches via evaluating the quality of pattern of sway [34-36]. It has been shown that this method is also sensitive to be used clinically for studying both typical and pathological development of motor control [33, 34]. This method has been used in some researches on subjects with Parkinson disease, however there is no study that used this approach on SCI individuals [37].

Correlation dimension, approximate entropy and Lyapunov exponent are some parameters used to evaluate stability based on nonlinear approach [38, 39]. Correlation dimension (CD) is a method to evaluate the number of degree of freedom during posture and provides dimensionality of the COP time series. It measures how the data points in a time series from a dynamic system are organized within a base of support. Decrease in CD significantly shows a decrease in dimensionality, which reports reduction in degree of freedom [34]. In contrast, increase in CD represents increase in adoptability or flexibility in maintaining postural control over the base of support. Approximate Entropy (ApEn) is a non-linear analysis method developed by Pincus as a measure of complexity of time series data [38, 40]. It represents the degree of isolation of a system from the surrounding. Increase or decrease in the magnitude of approximate entropy has been concluded as a sign of neuromuscular pathology to control standing stability [41, 43]. Lyapunov exponent is defined as the average of exponential rates of divergence or convergence of near orbits in the state space [39]. Actually, this method is based on mathematical method used for diagnosis of a chaotic system [39, 41].

Based on the results of various studies, SCI individuals have a high rate of falling. Seventy-five percent of the participants in a survey based study mentioned at least one fall over the year in which 18% sustained fracture, and 45% had problems in undertaking their daily activities [44]. It has been shown that SCI individuals have a high level of fear of fall as a result of imbalances during standing and poor standing stability [44]. In the study conducted by Karimi et al., SCI individuals were more stable during quiet standing based on linear method of analysis. The excursions of COP of SCI individuals were 17.5 and 22.6 mm in the anteroposterior and mediolateral planes, respectively, compared to 22.5 and 56.7 mm for normal subjects [16]. However, SCI subjects encounter huge problems during standing [44]. To our knowledge, there is no research that used nonlinear method to compare the stability of complete and incomplete SCI individuals with normal people.

SCI individuals use various orthoses to improve their standing and walking [20, 45]. Stability is the ability of a subject to keep the body stable and to return it from an unstable position to a stable position [46]. The stability of SCI people is greatly reduced, which makes them prone to risk of falling [46, 47]. The reason is lack of ankle, hip, and/or step strategies against falling [45, 48]. SCI people try to stand and walk using various orthoses [49-54]. As mentioned earlier, previous studies have focused on evaluating the stability during quite standing and for a short period of time [22-24]. As a result, some researches showed that the stability of SCI individuals was even better than that of normal subjects who were using the new developed orthosis [55]. On the other hand, most of the falling occurs during walking [46]. Thus, the study of quite standing alone cannot be used to predict the risk of falling. The result of the previous studies showed that there is no correlation between dynamic and static stability [56]. Unfortunately, there is no study on dynamic stability of SCI subjects while walking with and without any assistive devices. The aim of this research was to study the static and dynamic stability of SCI individuals and to compare them with those of normal subjects. The nonlinear approach to study stability in SCI individuals may show some new solutions to improve their abilities, i.e. it may enable the researcher to find a good idea about the weak and strong dynamic positions of a SCI person when walking.

Methods

We considered the alpha and beta level, respectively to be 0.05 and 0.02 and we expected the effect size to be more than 1.2, then a sample size of 5 was sufficient for the study [57, 58]. The study included three groups, namely: normal (10 persons), complete SCI (5 persons) and incomplete SCI (5 persons). In each group, motor and sensory scores were collected according to the impairment scale of American Spinal Injury Association. Those SCI participants who had an injury lesion between T11 and L1 were included in the study. Detailed demographic characteristics of the participants are presented in Table 1. The paraplegic subjects stood with the use of Double Knee ankle foot (KAFO) and MTK-RGO orthoses. The MTK-RGO orthosis is a new orthosis developed for standing and walking by paraplegic subjects with a high level of injury [16, 59]. An ethical approval was obtained from Isfahan University of Medical Science Ethical committee. A consent form was signed by each participant before

Table 1: Demographic characteristics of the participants.

Participants	Age (year)	Mass (kg)	Level of injury	Height (m)	Time post injury (year)
Complete SCI subjects stood up with KAFO and MTK-RGO orthoses.					
A	27	87	T12	1.88	4.5
B	33	70	T11	1.75	1.9
C	30	71	T12	1.76	5
D	25	67	T12	1.75	8.5
E	43	68	L1	1.73	2.5
Incomplete SCI individuals					
A	27	78	T11	1.75	4
B	37	57	L1	1.72	1.8
C	37	65	T11	1.78	3
D	21	58	T12	1.68	3.1
E	31	57	T12	1.7	2.2
Normal subjects					
	26±4.5	73±8.5	-	1.75±0.12	-

data collection.

Equipment

A Kistler force plate (Kistler instrument Corp, Amherst New York USA) was used to measure the center of pressure (COP) during standing. Some variables such as the excursions of the COP in both anteroposterior and mediolateral planes (AP and ML), COP velocity in AP and ML planes, and total velocity were used for final analysis. At the same time, some nonlinear parameters such as embedding dimension, correlation dimension and approximate entropy (ApEn) in AP and ML planes were used for final analysis. The linear variables were measured by using the following equations.

$$\text{COPEAP(mm)} = X_{max} - X_{min} \quad (1)$$

$$\text{COP EML (mm)} = Y_{max} - Y_{min} \quad (2)$$

$$\text{VAP (mm/min)} = \frac{\sum^{n-1} \sqrt{(x_{i+1} - x_i)^2}}{t} \quad (3)$$

$$\text{VML(mm/min)} = \frac{\sum^{n-1} \sqrt{(y_{i+1} - y_i)^2}}{t} \quad (4)$$

$$\text{TV(mm/min)} = \frac{\sqrt{(\sum^{n-1} \sqrt{(x_{i+1} - x_i)^2})^2 + (\sum^{n-1} \sqrt{(y_{i+1} - y_i)^2})^2}}{t} \quad (5)$$

Where, COPEAP, COPEML, VAP, VML, and TV are the excursion of the center of pressure in the anteroposterior direction, excursion of the center of pressure in the mediolateral direction, velocity of the COP in the anteroposterior direction, velocity of the COP in the mediolateral direction and total velocity, respectively. Moreover, the force applied on the crutch was measured in this study (it was calculated by subtracting the force applied on foot from the total weight of the body).

The subjects were asked to stand on the force plate for one minute. They were asked to look straight forward while standing in a comfortable position. The test was repeated to collect 5 successful trials. It should be emphasized that the SCI subjects used orthoses along with a crutch. The data of the force plate were collected with the frequency of 120 Hz. The data were filtered using Butterworth low pass filter with cut-off frequency of 10 Hz. [17, 18]. The first 15 and the last 15 seconds of the data were ignored to remove the effect of sudden standing on the force plate and to reduce the effects of muscle fatigue.

Two types of nonlinear methods were employed to analyze COP pattern including correlation dimension (CD), and approximate entropy (ApEn) (embedding dimension was used to determine the number of planes necessary for other calculations). For each signal, reconstruction of state space has been done and embedding dimension was calculated by False Nearest Neighbors method described by Shelhamer [59]. The idea of reconstruction of space is to plot the state space of the signal in its delayed signals with time delay of L. The key idea in the choice of L is that the elements that make up an attractor point should be close enough in time that they loosely approximate a derivative and are dynamically related, yet far enough apart in time that they are not repetitive. Each point should capture some dynamic information about the system, and if the elements of that point are too close together, the information they provide will be redundant. Therefore, mutual information is a way for quantifying this question: what does the distribution of x(i) tells us about the distribution of x(i+L)?. The mutual information between a time series x(i) and its shifted version x(i+L) is computed for various values of L until the mutual information is minimized.

After obtaining the time delay, embedding dimension ought to be calculated. In general, if an attractor is reconstructed in an embedding space with too small dimension M, then points on the attractor that are actually far apart in space will appear artificially close together. The trajectories are compressed because the embedding space is not large enough for them to fully expand. These points appear close together in M dimensions but are actually far apart, in a higher-dimensional space are false neighbors. FNN quantifies this concept. To find out the actual embedding space, the state space in different dimensions by lagged vectors of the main signal should be plotted. As long as the distance between each two points of trajectory changes, embedding dimension should be increased and the actual embedding dimension is the value in which there is no changes in the distance of trajectory points [59].

CD can be used to evaluate how the data points in a time series from a dynamical system are organized within the state space. CD is defined as:

$$CD = \lim_{R \to 0} \frac{\log C(R)}{\log R} \qquad (6)$$

Where C(R) is the correlation sum and is calculated as follows:

$$CR = \frac{1}{N(N-1)} \sum_{i=1}^{N} \sum_{j=1\, j\neq i}^{N} \Theta R - \left|x_i - x_j\right| \qquad (7)$$

Where x(i) indicates the states embedded in the reconstructed state space, N is the number of data points and Θ... counts the number of trajectory points lying within the distance R of the point i.

The mathematical method used to calculate ApEn was the one used by Pincus and Kafman, which has been mentioned in several publications [38, 40, 60]. Here, the ApEn was defined as ApEn (m, r, N), in which m is the length of compared runs, r is a tolerance and N is input data points. The procedure for calculating ApEn is as follows:

Given a time-series of data u(1), u(2), . . . , u(N) from measurements form a sequence of vectors: x(1), x(2), . . ., x(N - m + 1) in Rm, defined by x(i) = [u(i), u(i + 1), . . ., u(i + m - 1)].

Define for each *i*, 1≤i≤n-m+1:

$$C_i^m(r) = \frac{\text{number of } j \text{ such that } d[x(i),x(j)] \leq r}{N-m+1} \qquad (8)$$

where:

$$d[x(i),x(j)] = \max(|u(i+k-1) - u(j+k-1)|), \quad k=1,2,\ldots,m \qquad (9)$$

Define: $\Phi^m(r) = \frac{1}{N-m+1} \sum_{i=1}^{N-m+1} \log C_i^m(r)$ (10)

Then:

$$\mathrm{ApEn}(m,r,N) = \Phi^m(r) - \Phi^{m+1}(r) \qquad (11)$$

The tests were repeated to collect 3 successful trials. The data was collected with a frequency of 120 Hz. The signal of the force plate was filtered with a Butterworth low-pass filter of 10 Hz. The subjects were asked to stand on the force plate for a minute. The first and last 15 seconds of the data were removed and only 30 seconds of data were used for final analysis.

Data Analysis

The symmetry of distribution of the data was evaluated using box and whisker plot. Data were analysed by one-way ANOVA and post-hoc analysis by Tukey HSD method.

Results

Tables 2 and 3 summarize the stability analysis based on linear and non-linear methods, respectively. Based on Table 2, there was no significant difference among the stability of the groups in mediolateral direction, but there was a significant difference in all other values (P<0.05). The mean value of COP sway and corresponding velocities are the least for normal patients and the most for incomplete SCI groups. Compared to complete SCI group, the values in incomplete SCI group are higher due to the use of orthoses and crutch. Complete SCI group stood up with the use of KAFO and reciprocal gait orthosis (RGO) orthoses, whilst incomplete SCI group used no orthosis. Incomplete SCI group applied almost 10% of their body weight on crutch, whilst this Figure 1 was nearly 6% in complete SCI group.

The non-linear analysis method was also used to study the dynamic stability. Table 3 summarizes the stability analysis based on non-linear method. According to Table 3, the only significant differences were found in anteroposterior correlation dimension and mediolateral ApEn (P<0.05). The mean of anteroposterior correlation dimension was the least for normal group and the mean of mediolateral ApEn was the most for them. The mean of anteroposterior correlation dimension was the most for incomplete SCI group and the mean of mediolateral ApEn was the least for them. Figure 2 indicates the approximate entropy pattern of normal, incomplete and complete SCI, respectively.

Discussion

Stability is the ability of a subject to stand upright and to return the body from an unstable position to a stable position [61]. Most of the SCI subjects stand to improve their physiological health or to perform various hand tasks [19, 20]. However, their stability is not comparable

Table 2: Stability analysis based on linear method.

Parameter	**Mediolateral COP sway (mm)**	**Anteroposterior COP sway (mm)**	**COP velocity in AP (mm/s)**	**COP velocity in ML (mm/s)**	**Total velocity (mm/s)**
Normal	14.2 +13.2	20.6 +10.0	916+197	934+254	22.1+3.89
Incomplete SCI	22.1+8.7	50.8+17.8	1485±578	1760+340	38.7+10.14
Complete SCI	21.5 +15.9	25.5+22.8	1064+187	1291+285	27.9+5.56
F	1.1267	9.4008	7.8407	19.3294	18.5134
P-value	0.3389	0.0008*	0.0021*	0.0000*	0.0000*
Tukey HSD Post-hoc Test					
Normal vs. Inc.	0.4592	0.0005*	0.0014*	0.0000*	0.0000*
Norma vs. Com.	0.5130	0.7638	0.5753	0.0372*	0.1083
Inc. vs. Com.	0.9971	0.0209*	0.0693	0.0297*	0.0123*

Table 3: Stability analysis based on non-linear method.

Parameter	Embedding Diversion Mediolateral	Embedding Diversion Anteroposterior	Correlation Dimension in Anteroposterior	Correlation dimension in mediolateral	ApEn in anteroposterior	ApEn in mediolateral
Normal	3.4+0.5	4.2+1.3	3.5+0.4	3.3+0.8	0.21+0.15	0.41+0.08
Incomplete SCI	4.5+1.5	4.4+1.4	4.4+0.8	4.3+0.8	0.13+0.08	0.26+0.08
Complete SCI	4.3+1.6	4.3+1.5	4.3+0.9	4.0+0.8	0.22+0.06	0.27+0.08
F	3.8078	0.0483	7.3939	3.9388	0.8206	10.9701
P-value	0.0349	0.9530	0.0027*	0.0316	0.4509	0.0003*
Tukey HSD Post-hoc Test						
Normal vs. Inc.	0.0680	0.9526	0.0108*	0.0478*	0.4543	0.0024*
Norma vs. Com.	0.1554	0.9879	0.0247*	0.2056	0.9874	0.0045*
Inc. vs. Com.	0.9400	0.9924	0.9588	0.8251	0.5335	0.9787

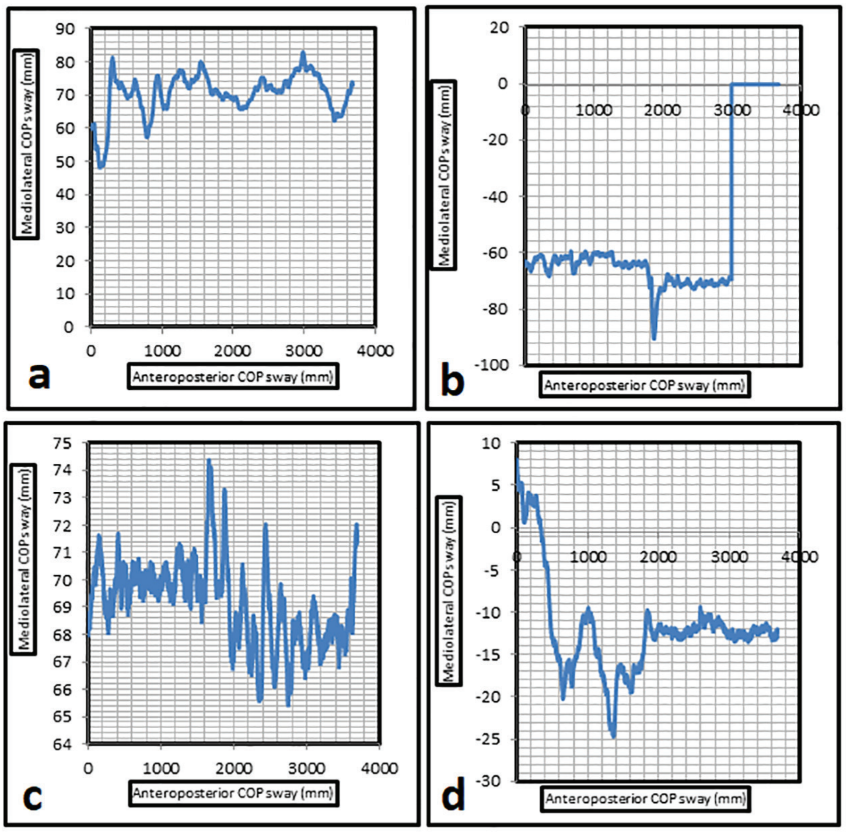

Figure 1: The COP sway of a normal (a) an incomplete SCI (b) and a complete SCI while standing with MTK-RGO (c) and KAFO orthoses, respectively.

with that of normal subjects [44]. Moreover, they depend on walker to stabilize their body or put the body in C posture which is not a suitable position for paralyzed standing and they cannot execute hand tasks in this position [23, 62]. In most of the previous studies, the stability of SCI subjects was evaluated while standing with an orthosis based on linear method [16, 22, 24]. However, the use of these parameters represents a limited information regarding stability [33, 39]. In this paper, it was aimed to evaluate stability of SCI subjects (complete and incomplete) with both linear and nonlinear methods and to represent possible solutions which can be used to improve their stability.

Table 2 represents the static stability during quiet standing. The results show that they were more unstable in anteroposterior direction and need to use walker to stabilize themselves in standing position (nearly 10% of BW was applied on walker). This indicates that the lack of the ankle mechanism is a big problem in this group of subjects. Therefore, they have to control their stability by using a C posture and a crutch or walker [23]. Linear method represents the quality of stability, therefore they show that the subjects are stable in ML and unstable in AP (but subjects can solve the instability in AP by the use of crutch).

Correlation dimension (CD) was the other parameter used to measure stability in this research. The mean values of CD in SCI individuals increased significantly compared to normal subjects. This represents an increase in freedom of subjects and their adoptability or flexibility in maintaining postural control over the base of support. Moreover, it shows that the subjects could use the new skills in order to stabilize themselves. The new skills which subjects used include the use of C posture and use of their upper limbs (and also crutch).

Approximate entropy was the other parameter used in this study, which is the method to determine the complexity of a time series and represents the regularity

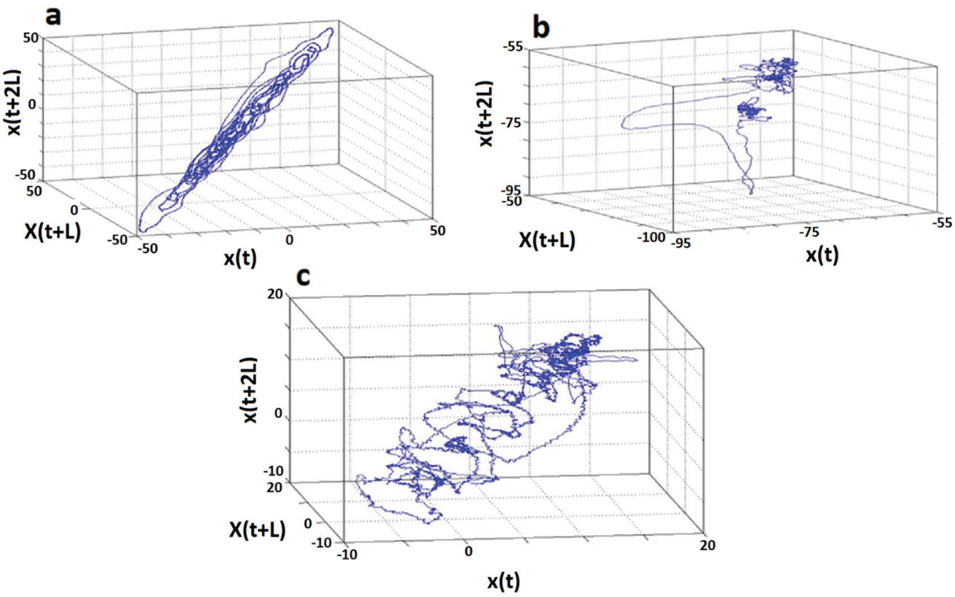

Figure 2: Reconstructed state space of COP of a normal (a) an incomplete (b) and a complete (c) SCI individuals.

of a system [33-35]. Higher value of this parameter indicates the irregularity of a system or explains increased dynamic control. The value of this parameter represents both regularity and inability of a system to move around and stabilize itself [33-35]. As can be seen from Table 4, both ML and AP values of ApEn decreased significantly, which represented more regularity of COP in SCI subjects. Increased regularity of COP time series is interpreted as an indication that the postural control system was more constructed after injury as a result of either mechanical stiffness or neurological impairment [33, 34]. In incomplete SCI, decrease in ApEn value means that although the subjects appear to be more stable than normal, but they had no ability to provide a dynamic stability. Based on all of these mentioned above, it can be concluded that the incomplete SCI individuals have some problems in stabilizing their body in standing position because of lack of ankle strategy, but they learned some skills such as putting the body in a C posture and using upper limbs and crutch to stabilize themselves. However, they lack the abilities to enhance a dynamic stability which is needed to perform hand tasks during standing.

The stability of complete SCI individuals standing with an orthosis improved especially in anteroposterior direction (no difference between stability of SCI and normal subjects in this plane). The main reason is related to the control of the motion of ankle joint with the orthosis. The stiffness of the orthosis around the ankle joint improves the stability of the SCI subjects [16]. The results on nonlinear analysis showed that the complete SCI subjects standing with orthosis can stabilize themselves but they do not need to employ other skills such as the use of upper limb and crutch force, the same as incomplete SCI subjects to stabilize themselves (there was no difference between these parameters between normal and complete SCI subjects) [62]. Therefore, it can be concluded that some specific parameters of the orthosis such as stiffness of the orthosis around ankle joint and or the use of trunk section of RGO orthosis improved the stability of the subjects [23, 25, 27]. However, as the value of coloration dimension in AP place differed from that of normal subjects, it can be conducted that the SCI subjects also need to use C posture to stabilize themselves (the hip joint has some degree of motion in RGO and there was no restriction for motion of hip joint in KAFO orthosis). The results of ApEn analysis also revealed that complete SCI subjects had more regularity in ML plane, which represented lack of dynamic stability [33]. However, their ability to have a dynamic stability in AP plane improved significantly (no difference between this parameter in normal and SCI subjects). Therefore, it can be concluded that the use of orthosis improves the abilities of subjects during standing due to stiffness of the ankle and hip joint. The need for subjects to use crutch and/or C posture decreases following the use of orthosis.

Although the stability of the subjects using orthosis improved, they need to use crutch. Moreover, the SCI subjects should stand when performing hand tasks or for therapeutic benefits, which takes a lot of time. Therefore, it is important to employ other methods to improve the stability of these subjects. As in human body the stability is controlled mainly by ankle strategy, it can be emphasized to focus on the other strategies in SCI subjects. Therefore, it is suggested to use an ankle foot orthosis with special actuators to control the stiffness of the ankle joint and to put this joint in a stable position to improve the standing performance of subjects. Some parameters such as the movement around ankle joint, and the location of COP can be used to control the stiffness of the system provided by the AFO.

There is a limitation which needs to be acknowledged in this study. The number of subjects was limited. Therefore, it is recommended that the same study should be conducted in future with a larger number of subjects.

Conclusion

Although SCI individuals can stabilize themselves by using crutch or putting their body in C posture, they have problems to stabilize themselves dynamically. The results of nonlinear analysis showed that SCI subjects have less ability to stabilize themselves during standing position. The use of orthosis improves their abilities to stand but they need to use crutch, which decreases their hand function. It is recommended that SCI (both complete and incomplete) subjects use an orthosis with a specially control system to enable them stand for a long time and perform various hand tasks.

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