Functional Electrical Stimulation vs. Voluntary Muscle Contraction: A Comparison Between Able-Bodied and People with Spinal Cord Injury

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Abstract

Fourteen Spinal Cord Injured (SCI) and 15 Able-bodied (AB) individuals participated in two 30 minutes (min) standing sessions. The control groups (SCICONT, ABCONT) consisted of both AB and SCI standing still with no muscle contraction. The experimental groups consisted of both SCI subjects (SCIEXP) standing with use of Functional Electrical Stimulation (FES)-induced muscle activation of four lower limb muscle groups and AB subjects (ABEXP) standing while performing tiptoe exercises for 30 min. A computerized impedance cardiograph was used to measure the changes of heart rate (HR), stroke volume (SV), cardiac output (CO), systolic, diastolic and mean arterial blood pressure (SBP, DBP, MAP) and total peripheral resistance (TPR) during sitting, and at 0, 5 and 30 min of standing. Change in position from sitting to standing caused significant drop in SBP, DBP, and MAP during SCICONT, while these values were maintained during SCIEXP. There were no significant changes in AB subjects in BP values. During SCIEXP standing, SCI maintained their hemodynamics at pre standing values at 5 min and 30-min post standing. These values decreased significantly during SCICONT, while TPR increased. The Able-bodied (AB) responded during ABCONT by a significant drop in SV and CO while TPR only increased at 30 min of standing. It was concluded that FES has equal or even better effect on improving blood circulation during standing than voluntary activation of the physiologic muscle pump and may be used to improve tolerance to tilting and standing in SCI.

Introduction/Background

When an individual moves from a sitting to an upright position there is a significant and instant shift in the fluid to the lower extremities, while full hydrostatic pressure exerts its influence on the arterial and venous columns. Under normal circumstances, blood pressure below the heart increases by approximately 90 mmHg, while it decreases by approximately 24 mmHg above the heart and in the skull.[1, 2] If the person stands still for about 20 to 30 min, 15 to 20% of the total blood volume may be pooled in the lower extremities and 10 % of plasma volume may be lost to the surrounding tissues.[1] As a result central and circulating blood volume decreases leading to significant reduction in stroke volume (SV), cardiac output (CO), blood pressure (BP), and an increase in heart rate (HR).[2] The normal body's response to maintaining blood flow to the vital organs and to maintaining BP during this change in position are a combination of central and peripheral responses. Lower limb muscle contractions, also called physiologic skeletal muscle pump, provides pressure against veins and aids the venous valves in returning venous blood to the heart. This increases the pre-load of the heart and eventually an increase in the after-load will increase the SV, CO, and BP. The end result will be a more stable BP (prevent orthostatic hypotension) and more tolerance to standing.[1, 3-5]

Following spinal cord injury (SCI), major physiological changes occur that can lead to disruption of sympathetic pathways, the inability of supraspinal vasomotor centers to respond to cardiovascular reflexes that alter vascular tone, and volitional muscle control which prohibits physiological muscle pump activation. The results of these changes include accumulation of venous blood in the lower extremities, reduction in the pre-load of the heart, and significant reductions in SV, CO, and BP during position change (i.e., standing or tilting).[6, 7] The eventual outcome would be intolerance to tilting and standing and the symptoms of orthostatic hypotension would prevail.

Functional electrical stimulation (FES) has been used to artificially stimulate the contraction of lower extremity skeletal musculature and to improve venous return to the heart and to reduce venous stasis during exercise in SCI and in supine during anesthesia.[5, 7, 8] The results have shown significant increases in SV, CO, and BP.

The purpose of the present study was to compare the hemodynamic responses to changes in position and standing between a group of Able-bodied (AB) and SCI subjects. We further evaluated the effect of the physiologic muscle pump during standing on central hemodynamics of both groups. We hypothesized that both groups would have reductions in central circulation following 30 min of standing and that FES-induced activation of the physiologic muscle pump in SCI subjects would produce the same hemodynamic response as voluntary contraction.

Methods

Subjects: Fourteen healthy SCI individuals levels C3 to T12 complete or incomplete, 6 months post-SCI were recruited for this study. Eleven males and 3 females

were recruited for the study (7 paraplegics and 7 tetraplegics). The mean±SD for age was 35 ± 10.2 years. Fifteen healthy AB subjects (7 males and 8 females (29.7 ± 6.2 years) were also recruited. All subjects signed an informed consent and were medically evaluated by a physician.

Procedures: All subjects participated in two sessions of 30 min. standing. The first session consisted of control standing of both AB and SCI subjects (ABCONT, SCICONT), where each subject stood passively without intervention. The second session, on a separate day, consisted of AB and SCI standing while activating the physiologic muscle pump (SCIEXP, ABEXP). During ABEXP, AB subjects performed tiptoe exercises (11-second (sec) contraction 60-sec rest). During SCIEXP, SCI subjects received bilateral FES-induced contractions of the quadriceps (QU), hamstrings (HA), gastrocnemius (GA), and tibialis anterior (TA) muscles. The FES contraction started while sitting and continued throughout standing. The timing for FES-induced activation of lower limb muscles was 11-sec co-contraction of GA and TA followed by 4-sec co-contraction of QA and HA, with a 7-sec overlap of contraction of all four muscles, followed by 60 sec of rest. This protocol was used to induce a milking effect and to move the blood from the lower limb to the heart.

Two Empi Respond Select Dual Channel Neuromuscular Electrical Stimulators (Empi Inc., St. Paul, MN) with bifurcated leads were utilized for each SCI subject. Two surface electrodes were used to stimulate each muscle. Both groups used the EasyStand™ 5000 (Altimate Medical , Inc., Morton, MN 56270 USA) device during the two standing sessions. This system provided an optimal level of head support, height, safety belt, arm support, abdominal pad and arm support, lateral support, hip guide, and shoulder support.

Measurements: A computerized impedance cardiograph CIC -1000 (SORBA Medical System, Inc., Brookfield, WI) was used to measure the hemodynamic changes of HR, SV, CO, CI, BP, and TPR. Data recorded during sitting, and at 0, 5 and 30 minutes (min) of standing.

Data analysis: Repeated measures analyses of variance (ANOVA) was used and appropriate multiple comparison tests were followed to evaluate changes from standing at time zero to 5 and 30 min of standing. T-tests were used to evaluate changes from sitting to standing and percentage changes were reported. The BMDP statistical software package (Dixon,1990) and SPSS (version 6.1) were used for data analysis. All alpha levels were at $p \leq 0.05$.

Results

The results of the hemodynamic responses during change in position from sitting to standing and from time zero during standing at 5 and 30 min are depicted in table 1 (A-C). The *p* values are also shown in the table.

Sit to stand (A)				
P	**SCI/CONT**	**SCI/EXP**	**AB/CONT**	**AB/EXP**
HR	**+16**	**+10**	**+7**	**+5**
P	***0.001***	***0.010***	***0.001***	***0.010***
SV	**-13**	**-20**	**-17**	**-13**
P	***0.001***	***0.001***	***0.030***	***0.050***
CO	**+1**	**-14**	**-10**	**-8**
P	***0.230***	***0.001***	***0.040***	***0.040***
TPR	**+8**	**+20**	**+8**	**+5**
P	***0.120***	***0.030***	***0.130***	***0.170***
SBP	**-8**	**-0.7**	**-3**	**-2**
P	***0.001***	***0.460***	***0.020***	***0.070***
DBP	**-9**	**+2**	**0.7**	**-3**
P	***0.007***	***0.370***	***0.320***	***0.070***
MAP	**-8.5**	**+0.80**	**-2**	**-2**
P	***0.002***	***0.450***	***0.110***	***1.40***

5 minutes of standing (B)				
P	**SCI/CONT**	**SCI/EXP**	**AB/CONT**	**AB/EXP**
HR	**+2**	**+1**	**+5**	**+3**
P	***0.16***	***0.770***	***0.001***	***0.060***
SV	**-13**	**+5**	**-9**	**-7**
P	***0.002***	***0.260***	***0.010***	***0.060***
CO	**-12**	**+5**	**-5**	**-3**
P	***0.005***	***0.200***	***0.060***	***0.230***
TPR	**+12**	**-2**	**+5**	**+5**
P	***0.012***	***0.370***	***0.130***	***0190***
SBP	**-0.21**	**+2**	**+1**	**-1.3**
P	***0.460***	***0.210***	***0.320***	***0.120***
DBP	**+1.3**	**+2**	**+0.2**	**-0.4**
P	***0.310***	***0.260***	***0.420***	***0.430***
MAP	**+0.7**	**+2**	**+0.6**	**-0.8**
P	***0.370***	***0.230***	***0.180***	***0.270***

10 minutes of standing (C)				
	SCI/CONT	**SCI/EXP**	**AB/CONT**	**AB/EXP**
HR	**+4**	**+11**	**+11**	**+7**
P	***0.050***	***0.010***	***0.003***	***0.030***
SV	**-24**	**-16**	**-24**	**-17**
P	***0.008***	***0.007***	***9.96***	***1.30***
CO	**-22**	**_6**	**-14**	**-13**
P	***0.003***	***0.110***	***0.003***	***0.001***
TPR	**+25**	**+6**	**+20**	**+18**
P	***0.010***	***0.240***	***0.001***	***0.140***
SBP	**+1**	**-6**	**+3**	**-0.3**
P	***0.420***	***0.150***	***0.090***	***0.340***
DBP	**+3**	**0.7**	**+4**	**+2**
P	***0.230***	***0.430***	***0.030***	***0.220***
MAP	**+2.6**	**-3**	**+3**	**+0.18**
P	***0.380***	***0.260***	***0.320***	***0.440***

Table 1: A, B, C: Percentage change in heart rate (HR), stroke volume (SV), cardiac output (CO), total peripheral resistance (TPR), systolic blood pressure (SBO), diastolic blood pressure (DBP), and mean arterial pressure (MAP) from sitting to standing position, after 5 minutes and 30 minutes of standing in Spinal cord injured (SCI) and Able-bodied (AB) subjects during 30 minutes of control (CONT) and experimental (EXP) standing. SCI FES-augmented standing (SCIEXP), SCI no FES augmented standing (SCICONT), AB standing while

performing tiptoe contraction (ABEXP), and AB standing without muscle contraction (ABCONT). (Values of significance, P ≤ 0.05).

Change in position caused significant drop in SBP), DBP, and MAP during SCICONT, while these values were maintained during SCIEXP. There were no significant changes in AB subjects in BP values. During SCIEXP, SCI maintained all the hemodynamics at pre-standing values during 5 min and after 30 min of standing. These values decreased significantly during SCICONT, while total peripheral resistance (TPR) increased. AB responded during ABCONT by significant drops in SV and CO while TPR only increased at 30 min of standing. Values were maintained at pre standing values for ABEXP after 5 min of standing; however, CO decreased while HR and TPR increased.

Discussion/Conclusions

The results of this study demonstrated that the addition of FES to individuals with SCI during standing prevented circulatory hypokinesis. The central hemodynamic variables CO, SV, and TPR were more stable during 30 min of FES standing than during standing without intervention. Using FES during the transition from sitting to standing prevented a decrease in blood pressure in these subjects. During the SCICONT, when subjects were moving from the sitting to the standing posture, there was a significant decrease ($p<0.05$) in all blood pressure measures. However, all of the BP's were maintained during SCIEXP. This was consistent with the finding in our AB subjects. It appears that the addition of FES-contractions of muscle during changes in position from sitting to standing might have caused venous blood to return to the heart and result in a stale BP. Although this observed decrease in BP from sitting to standing during the control standing condition would not be considered "orthostatic hypotension", since the decrease was less than 10% and blood pressure was usually around or above 70/40 mmHg [8,9] However, it should be noted that a 9% increase in blood pressure could have a major impact on orthostatic hypotension in a tetraplegic subject, with blood pressure lower than 70/40 mmHg.

After 5 min of SCICONT, SV and CO declined by 14%, and after 30 min, they further declined by: 24%, and 22%, respectively. During SCIEXP, the SCI individuals demonstrated no significant changes in central hemodynamics after five min., which was consistent with our AB subjects during ABEXP. After 30 min of SCIEXP all variables remained stable, except for a 16% decline in stroke volume and an 11% increase in HR. This HR response in part accounts for the more stable CO, as CO is the product of SV and HR. Total peripheral resistance significantly increased during SCICONT, while it did not change during SCIEXP. The increase in TPR during SCICONT, as well as ABCONT and ABEXP, is a compensatory mechanism to maintain the BP and blood flow to the vital organs during standing. During SCIEXP, TPR did not change. This is an important finding and could be an indication that while FES provided an effective pump to move the blood to the central circulation and; therefore, maintain the circulation, it may have also improved the arterial circulation to the stimulated muscle. This has also been reported by previous investigators.[5, 10]

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