Altered resting hemodynamics in lower-extremity arteries of individuals with spinal cord injury

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Objective: To investigate lower-extremity arterial hemodynamics in individuals with spinal cord injury (SCI). We hypothesized that oscillatory shear index would be altered and resting mean shear would be higher in the lower-extremity arteries of SCI.

Research: Cross-sectional study of men and women with SCIs compared to able-bodied controls.

Subjects: Subjects included 105 ages 18–72 years with American Spinal Injury Association (ASIA) Impairment Scale grades A, B, or C and injury duration at least 5 years. Subjects were matched for age and cardiovascular disease risk factors with 156 able-bodied controls.

Methods: Diameter and blood velocity were determined with subject at rest via ultrasound in superficial femoral, popliteal, brachial, and carotid arteries. Mean shear, antegrade shear, retrograde shear, and oscillatory shear index were calculated.

Results: Oscillatory shear index was lower in SCI compared to controls for superficial femoral (0.16 ± 0.10 vs. 0.26 ± 0.06 , $P < 0.01$) and popliteal arteries (0.20 ± 0.11 vs. 0.26 ± 0.05 , $P < 0.01$). Mean shear rate was higher in SCI compared to controls for superficial femoral (43.54 ± 28.0 vs. 20.48 ± 13.1 /second, $P < 0.01$) and popliteal arteries (30.43 ± 28.1 vs. 11.68 ± 9.5 /second, $P < 0.01$).

Conclusions: The altered resting hemodynamics in SCI are consistent with an atheroprotective hemodynamic environment.

Keywords: Atherosclerosis, Hemodynamics, Peripheral artery disease, Spinal cord injuries, Paraplegia, Tetraplegia, Rehabilitation, Disability

Introduction

Rapidly following spinal cord injury (SCI), extensive vascular adaptations occur below the level of injury¹ with much smaller adaptations occurring in the upper-extremity arteries in the long term.² These extensive changes in the lower-extremity arteries may better explain increased cardiovascular disease risk³ in individuals with SCI. In individuals with SCI, the lower-extremity artery adaptations include significant reductions in lower-extremity artery diameter¹ and increases in mean blood velocity,⁴ which produce mean wall shear rates that are approximately double those reported in able-bodied individuals.^{1,5,6} Elevated mean shear has been reported to produce an anti-atherogenic endothelial

cell phenotype in both cell culture and isolated vessel preparations.⁷ Consistent with this anti-atherogenic endothelial cell phenotype are reports of increased endothelial function and decreased intima-media thickness with increasing shear rates in able-bodied individuals.^{8,9} Interestingly, SCI has been reported to result in a reduction of endothelial function^{5,10–12} in some, but not all, of the lower-extremity arteries of individuals with SCI. Furthermore, SCI has been reported to produce an increase in intima-media thickness in some of the lower-extremity arteries of people with SCI.² Unfortunately, reports of altered arterial structure and hemodynamics in individuals with SCI have used relatively small populations, and are mostly limited to the common and superficial femoral arteries.^{1,4,12} For this reason it is difficult to generalize these changes to larger populations and other lower-extremity arteries

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affected by SCI. Regardless, the discrepancies in responses to mean shear between able-bodied and individuals with SCI suggest that other hemodynamic stimuli may influence reported group differences in artery structure and function.

Differences in lower-extremity artery shear pattern following SCI may account for the previously described discrepancies in vascular structure and function between able-bodied and individuals with SCI. It is well recognized that laminar and oscillatory shear patterns produce distinct phenotypes.^{13–17} Specifically, oscillatory shear reduces endothelial function and produces a pro-atherogenic gene expression pattern consisting of increased adhesion molecules, superoxide production, and monocyte recruitment.^{14–17} Unfortunately, due to a paucity of literature in this area it is challenging to determine the impact that oscillatory shear plays in the maladaptive vascular structure reported in the lower-extremity arteries of SCI. Therefore, the purpose of this investigation was to elucidate hemodynamic differences in lower-extremity arteries of individuals with SCI compared to able-bodied individuals.

Materials and methods

Subjects

This investigation utilized the same subjects from a previous study investigating the prevalence of lower-extremity peripheral arterial disease in SCI.² SCIs ($n = 105$) were recruited and tested from a SCI rehabilitation program and through wheelchair recreation and sporting groups in the midwestern and southern USA. Able-bodied individuals from similar geographic regions served as controls ($n = 156$). Subjects were excluded for hemiplegia, but were not excluded for presence of other diseases such as cardiovascular disease or diabetes. As previously reported,² SCI and able-bodied control groups were similar in age (40.6 ± 12.0 vs. 41.6 ± 10.9 years), sex (88.6% vs. 86.0% male), height (178 ± 8.8 vs. 178 ± 10.9 cm) and systolic blood pressure (123.3 ± 12.3 vs. 126.5 ± 18.5 mmHg). Alternatively, individuals with SCI weighed less (79.9 ± 19.8 vs. 86.0 ± 18.7 kg) and had lower body mass indexes (25.4 ± 5.3 vs. 27.0 ± 5.5 kg/m²). In addition, individuals with SCI reported greater smoking behavior (28.6 vs. 10.9%). Individuals with SCI were at least 5 years post-injury (19.3 ± 8.9 years) and included participants with paraplegia ($n = 74$) and tetraplegia ($n = 31$) having injuries classified as American Spinal Injury Association (ASIA) Impairment Scale grades A ($n = 70$), B ($n = 11$), or C ($n = 24$).¹⁸ Individuals with impairment scores of C were included if they were non-ambulatory during the

largest extent of their day excluding during transfers and therapeutic walking. In individuals with SCI, lesions were at levels between C4 and L1. Medication usage for these subjects have been described previously.² Briefly, 43.8% of individuals with SCI reported central nervous system depressant, muscle relaxant, or anticonvulsant usage, 28.6% used bladder medication, 16.2% reported laxative usage, 21.9% utilized non-steroidal anti-inflammatory or oral analgesics, and 13.3% reported medication usage for erectile dysfunction in comparison with controls who reported 5.8, 5.1, 0.0, 9.6, and 0.0%, respectively. Prior to participation, each subject was informed of the study's objectives, measurement techniques, and potential risks or discomforts, and signed written informed consent. The Institutional Review Boards of both Northwestern University and Purdue University approved this study.

Experimental protocol

As previously reported, all procedures were completed within a single testing session and included hemodynamic measurements of four arteries.² Subjects were not required to arrive for testing in a fasted state nor were they required to abstain from caffeine, tobacco, or medication usage prior to testing. The lower-extremity arteries of interest included the superficial femoral and popliteal arteries. In the upper-extremities, the brachial and carotid arteries served as a control since blood flow to these arteries measured at rest are reported to be similar between individuals with SCI and able-bodied individuals.¹⁹ During testing, subjects rested supine for at least 15 minutes before artery diameter and red blood cell velocity was measured via Doppler ultrasound in each subject's superficial femoral, popliteal, brachial, and carotid arteries. Artery characteristics were measured with the subject resting supine excluding the popliteal which was measured with the subject resting prone. Anatomical landmarks for ultrasound imaging were previously described.² Briefly, the superficial femoral artery was imaged in the subsartorial canal distal to the bifurcation of the common femoral artery. Popliteal artery images were obtained in the popliteal fossa superior to the bifurcation into the anterior and posterior tibialis arteries. All testings were performed by the same investigator.

Measurements

Artery diameter measurements were performed as previously described.² Briefly, the diameter was determined via ultrasound (Terason T3000, Burlington, MA, USA) utilizing a variable-frequency transducer

(5–12 MHz). Artery diameter was not determined in real-time; instead, a 10-second video file was recorded at a rate of 15 Hz using screen video capture software (Camtasia, Techsmith, Okemos, MI, USA). Offline analysis was performed for the entire duration of the 10-second video file using automated edge-detection software capable of detecting the lumen-media interfaces (Medical Imaging Applications LLC Brachial Analyzer 5, Coralville, IA, USA). During each arterial diameter measurement, as previously described,²⁰ continuous Doppler antegrade and retrograde velocity corrected for an insonation angle of 60° was obtained with a large sample volume to encompass but not extend beyond each artery diameter. Instantaneous mean velocity was estimated from all Doppler shifts measured across the vessel using custom-designed software (MatLab, Mathworks, Natick, MA, USA). This software outputs time-averaged mean blood velocity, antegrade mean velocity, and retrograde mean velocity per cardiac cycle velocity waveform and mean velocity represents time-averaged antegrade velocity minus time-averaged retrograde velocity.

Hemodynamic calculations

Shear rates (per second) were used as a surrogate measure of shear stress²¹ and were calculated as $4 \times V_m / D$ where V_m is mean blood velocity (in centimeters per second) and D is arterial diameter. Oscillatory shear index was used as an indicator of the magnitude of shear oscillation and was defined as $OSI = |\text{retrograde shear}| / (|\text{antegrade shear}| + |\text{retrograde shear}|)$. Using this formula, a unidirectional shear pattern corresponds to an index of 0.0 and pure oscillation is represented by 0.5.²²

Statistical analysis

Using commercially available programs (SAS versions 9.1 and 9.2, SAS, Cary, NC, USA), a one-way analysis of variance with a Tukey–Kramer adjustment for multiple comparisons was performed using PROC GLM to determine group differences between individuals with SCI and control groups. When variables were not normally distributed, in the case of all retrograde velocity measurements and related calculations, ranks transformation was performed prior to analysis. All data are presented as mean $\pm$ standard deviation. Statistical significance was established *a priori* as $P < 0.05$.

Results

Lower-extremity arteries

Table 1 summarizes the resting artery diameter, mean blood velocity, antegrade velocity, and retrograde velocity in the superficial femoral and popliteal arteries of individuals with SCI and controls. Arterial diameters are presented as previously reported.² The superficial femoral artery mean shear rate was 113% greater in individuals with SCI compared to controls (Fig. 1, $P < 0.01$). This difference is reflected in a 22% smaller diameter in individuals with SCI compared to controls (Table 1, $P < 0.01$) combined with a 35% greater antegrade velocity (Table 1, $P < 0.01$) and 46% smaller retrograde velocity (Table 1, $P < 0.01$) that yielded a 72% greater mean velocity (Table 1, $P < 0.01$). In addition, in the superficial femoral artery of individuals with SCI there were significantly larger antegrade shear rates (Fig. 2, $P < 0.01$) and significantly smaller retrograde shear rates (Fig. 3, $P < 0.01$). These antegrade

Table 1 Blood velocity characteristics

Artery	Variable	SCI	Controls	P value
SFA	Diameter, mm	5.38 $\pm$ 0.94	6.89 $\pm$ 1.04	<0.01
	Mean velocity, cm/second	5.83 $\pm$ 3.84	3.38 $\pm$ 1.89	<0.01
	Ante velocity, cm/second	6.69 $\pm$ 3.39	4.96 $\pm$ 1.72	<0.01
	Retro velocity, cm/second	−0.86 $\pm$ 0.80	−1.59 $\pm$ 0.66	<0.01
PA	Diameter, mm	5.20 $\pm$ 0.91	6.71 $\pm$ 1.15	<0.01
	Mean velocity, cm/second	3.84 $\pm$ 3.46	1.89 $\pm$ 1.37	<0.01
	Ante velocity, cm/second	4.80 $\pm$ 3.11	3.05 $\pm$ 1.32	<0.01
	Retro velocity, cm/second	−0.96 $\pm$ 0.84	−1.16 $\pm$ 0.49	<0.01
BA	Diameter, mm	4.79 $\pm$ 0.88	4.47 $\pm$ 0.69	<0.01
	Mean velocity, cm/second	5.61 $\pm$ 3.55	5.08 $\pm$ 2.93	0.15
	Ante velocity, cm/second	5.89 $\pm$ 3.33	5.33 $\pm$ 2.76	0.11
	Retro velocity, cm/second	−0.28 $\pm$ 0.40	−0.25 $\pm$ 0.34	0.65
CA	Diameter, mm	7.23 $\pm$ 0.65	7.34 $\pm$ 0.67	0.22
	Mean velocity, cm/second	10.36 $\pm$ 2.71	9.91 $\pm$ 2.28	0.16
	Ante velocity, cm/second	10.37 $\pm$ 2.71	9.93 $\pm$ 2.23	0.17
	Retro velocity, cm/second	−0.01 $\pm$ 0.02	−0.02 $\pm$ 0.16	0.11

SCI, spinal cord injured individuals; Ante, antegrade; Retro, retrograde; SFA, superficial femoral artery; PA, popliteal artery; BA, brachial artery; CA, carotid artery.
Values are means $\pm$ SD.

Figure 1 Mean shear rate measured at rest in lower- and upper-extremity arteries of SCI and able-bodied controls. SFA, superficial femoral artery. Values are means $\pm$ SD. *SCI significantly different from control ($P < 0.01$).

Figure 2 Mean antegrade shear rate measured at rest in lower- and upper-extremity arteries of SCI and able-bodied controls. SFA, superficial femoral artery. Values are means $\pm$ SD. *SCI significantly different from control ($P < 0.01$).

Figure 3 Mean retrograde shear rate measured at rest in lower- and upper-extremity arteries of SCI and able-bodied controls. SFA, superficial femoral artery. Values are means $\pm$ SD. *SCI significantly different from control ($P < 0.01$).

Figure 4 Oscillatory shear index measured at rest in lower- and upper-extremity arteries of SCI and able-bodied controls. SFA, superficial femoral artery. Values are means $\pm$ SD. *SCI significantly different from control ($P < 0.01$).

and retrograde shear differences between SCI and controls yields a 63% smaller oscillatory shear index in individuals with SCI compared to controls (Fig. 4, $P < 0.01$).

Similar results occurred in the popliteal artery where mean shear rate was 161% greater in SCI compared to controls (Fig. 1, $P < 0.01$). In SCI, diameter was 23% smaller (Table 1, $P < 0.01$), antegrade velocity was 57% greater (Table 1, $P < 0.01$), retrograde velocity was 17% smaller (Table 1, $P < 0.01$), and the resultant mean velocity was 103% greater (Table 1, $P < 0.01$) compared to controls. Similar to the superficial femoral artery, popliteal artery antegrade shear was significantly greater (Fig. 2, $P < 0.01$). Alternatively, popliteal artery retrograde shear was not different in individuals with SCI compared to controls (Fig. 3, $P = 0.50$). Consequently, popliteal artery oscillatory shear index was 30% smaller in individuals with SCI compared to controls (Fig. 4, $P < 0.01$).

Upper-extremity arteries

Table 1 summarizes the resting artery diameter, mean blood velocity, antegrade velocity, and retrograde velocity in the brachial and carotid arteries of SCI and controls. Arterial diameters are presented as previously reported.² Interestingly, brachial artery diameter was 7% larger in SCI compared to controls, but there were no differences in carotid artery diameter (Table 1). Moreover, there were no differences in mean velocity, antegrade velocity, or retrograde velocity (Table 1). There were also no differences in mean shear (Fig. 1), antegrade shear (Fig. 2), retrograde shear (Fig. 3), or oscillatory shear index (Fig. 4) in the brachial or carotid arteries of SCI compared to controls.

Discussion

The altered hemodynamics reported in the literature for the lower-extremity arteries of individuals with SCI suggests that these arteries should have decreased susceptibility to atherosclerosis compared to able-bodied individuals. This is not consistent with reports of reduced arterial function and larger intima-media thickness normalized for artery diameter in lower-extremity arteries of SCI.^{2,5,10–12} To provide insight into these reported discrepancies between lower-extremity hemodynamics and atherosclerotic susceptibility in SCI, this study sought to thoroughly characterize the resting hemodynamic environment of lower-extremity arteries in a large sample of individuals with SCI. The findings from this study (1) confirm previous data^{5,6} suggesting that conduit arteries in the lower extremities of SCI are exposed to resting shear rates that are approximately double to those reported in able-bodied individuals and (2) demonstrate, for the first time, that oscillatory shear index is reduced in the lower-extremity arteries of individuals with SCI compared to able-bodied individuals. Our findings suggest that lower-extremity arteries of individuals with SCI can be characterized as having key components of an anti-atherogenic hemodynamic stimulus when compared to able-bodied individuals.

Mean shear rate

The few published studies in the literature suggest that SCI leads to structural and hemodynamic adaptations resulting in an increased mean shear within arteries affected by the SCI.^{1,5,23} In an investigation of 15 individuals with motor complete SCI, De Groot *et al.*¹ reported a 28% smaller diameter concomitant with a 100% greater mean shear rate in the common femoral artery of individuals with SCI. Similarly, a study of 10 individuals with SCI with paraplegia reported a 29% reduction in common femoral artery diameter with blood velocity double compared to able-bodied controls.⁴ Two smaller studies, with 6 and 11 individuals with motor complete injuries, respectively, indicate that in the superficial femoral artery, SCI compared to controls have a 29–35% smaller diameter and a 238–285% greater mean shear rate.^{5,23} Currently, no studies have reported diameter and mean shear rate for the popliteal artery of individuals with SCI compared to able-bodied individuals. Our findings of a 22 and 23% smaller diameter for the superficial femoral artery and popliteal artery, respectively, may be due to our investigation of 105 individuals with SCI, a much larger sample size than the reports described above. In addition, inclusion of motor incomplete lesions combined with the larger sample size may partially explain

the smaller magnitude of elevation in the superficial femoral artery mean shear rate (113 vs. 238–285%) compared to the literature. These findings are significant to our understanding of the role that hemodynamic mechanisms play in atherogenesis because historically it has been thought that greater mean shear is a key component of an atheroprotective hemodynamic environment.^{7,13} Specifically, acutely increased shear stimulates improved endothelial cell phenotype due to increased endothelial nitric oxide synthase and superoxide dismutase production as well as decreased endothelin-1 and vascular cell adhesion molecule-1 gene expression.⁷ Conversely, areas with low shear are associated *in vivo* with focal development of atherosclerotic lesions.²⁴ Therefore, the elevated mean shear rate occurring after motor complete and motor incomplete SCI theoretically should provide an atheroprotective hemodynamic stimulus to the lower-extremity conduit arteries affected by the injury.

Several hemodynamic components contribute to our finding that resting mean shear is elevated by 100% or more in the popliteal and superficial femoral arteries of SCI. In part, a higher mean shear can be attributable to the reduction in artery diameter that occurs within weeks of incurring the injury.¹⁹ For example, the findings in the present study of a 22–23% smaller superficial femoral and popliteal artery diameter in SCI are confirmed by previous cross-sectional comparisons of individuals with motor complete injuries and able-bodied controls, which report 28–35% smaller artery diameters in lower-extremity conduit arteries. Mathematically, smaller diameter would result in an increase of mean shear without alterations to mean blood velocity. In the current study, a substantial portion of the greater mean shear rate in SCI is driven by higher mean blood velocity. The approximate doubling of mean blood velocity in the superficial femoral and popliteal arteries confirms previous reports of 100% greater mean blood velocity in the common femoral artery.⁴ A closer analysis of the antegrade and retrograde components of mean shear reveals additional differences in individuals with SCI compared to able-bodied controls including 35–57% greater antegrade velocity with a 17–46% smaller retrograde velocity. To our knowledge, this is the first analysis that has identified the antegrade and retrograde velocity contributions to the elevated mean velocity and shear reported in the SCI literature. In summary, the greater antegrade shear combined with smaller diameter along with minor contributions from the retrograde shear appear to be driving the higher mean shear in lower-extremity conduit arteries of individuals with SCI. Interestingly, these antegrade

and retrograde components of mean shear not only affect the magnitude of mean shear rate, but also the magnitude of the oscillatory shear index.

Oscillatory shear index

Considering the antegrade and retrograde components of conduit artery mean shear, the current findings for elevated mean shear suggest that oscillatory shear index may also be altered in individuals with SCI. Oscillatory shear index was 63% smaller in the superficial femoral artery and 30% smaller in the popliteal artery in these individuals with SCI. To our knowledge, this is the first report of a smaller oscillatory shear index in SCI compared to able-bodied controls for the superficial femoral or popliteal artery, but our finding is consistent with reports of reduced oscillatory shear in the infrarenal aortic arteries of individuals with SCI.²⁵ As described above, antegrade shear was greater and retrograde shear was smaller in the superficial femoral artery whereas antegrade shear was greater with no differences in retrograde shear in the popliteal artery in individuals with SCI compared to controls. These changes in the antegrade and retrograde components of shear resulted in a reduced oscillatory shear index which is important because reversing, or oscillatory shear is implicated in atherogenesis. Specifically, oscillatory shear with blood flow reversal exerts effects through increased expression of adhesion molecules, monocyte adhesion,^{15,17,26} increased superoxide production,¹⁶ and impaired endothelial function.²⁷ Therefore, for individuals with SCI the reduction in oscillatory shear index suggests that the lower-extremity conduit arteries of these individuals contain an additional key component of an atheroprotective hemodynamic environment.

Several factors could explain the differences in oscillatory shear index between SCI and able-bodied controls. As previously described, the oscillatory shear index utilizes the magnitude of antegrade and retrograde shear to represent the extent of flow reversal. The differences in oscillatory shear index for individuals with SCI compared to controls are attributable to the greater antegrade shear and smaller retrograde shear in the superficial femoral artery, but only to the greater antegrade shear in the popliteal artery. It is unclear as to what underlying mechanisms may be causing these differences. However, Padilla *et al.*²⁰ recently reported that increased sympathetic outflow causes an increase in oscillatory shear index. These authors demonstrated that the alteration of oscillating shear patterns due to increased sympathetic outflow was attributable to decreased antegrade components and increased retrograde components of velocity and the resultant

shear.²⁰ Essentially, the opposite of these effects occurred in the lower-extremity arteries of individuals with SCI in the current study. Unfortunately, the current investigation included no measurements of sympathetic nervous system function in its individuals with SCI. This does indicate, however, that the reduced oscillatory shear index in SCI may be due to the removal or impairment of sympathetic innervation. Furthermore, because of the report by Padilla *et al.* that increased sympathetic outflow will reduce antegrade velocity and increase retrograde velocity,^{1,20} it is reasonable to assume that reduced sympathetic outflow may partially explain increased blood velocity and its contribution to elevating the mean shear rate in the lower-extremity conduit arteries of SCI.

Significance of findings

In this investigation, the superficial femoral and popliteal arteries of SCI exhibited an increased mean shear rate and reduced oscillatory shear index compared to able-bodied controls. These findings are consistent with a hemodynamic environment that contains key components of atheroprotection. However, the current finding for reduced oscillatory shear index in SCI is not consistent with our previous report that these arteries had greater normalized intima-media thickness.² Therefore, the hemodynamic environment does not likely contribute to the increased lower-extremity sub-clinical measurements of peripheral arterial disease reported in SCI. In addition, the potential for the smaller oscillatory shear index to be related to a reduction or removal of lower-extremity sympathetic function suggests that a reduction or removal of sympathetic outflow due to SCI may decrease athero-susceptibility in affected arteries. Other plausible mechanisms for the greater susceptibility to lower-extremity peripheral arterial disease include shear rate, shear pattern, and arterial circumferential stretch alterations that would be caused by normal lower-extremity muscular activity such as those occurring during ambulation. It is possible that other mechanisms yet to be investigated may also play a role.

Limitations

There are a number of limitations that may limit our ability to interpret these data. Perhaps the greatest limitation of this study is the employment of a cross-sectional design which does not allow for determination of causality. Second, shear stress is the established stimulus for vascular function and this study utilized measurements that allowed the calculation of shear rate. It is possible in this cross-sectional sample that there are differences

in blood viscosity between individuals with SCI and able-bodied individuals. However, Boot *et al.* reported no differences in blood viscosity between individuals with SCI and able-bodied controls and we do not believe that there would be a difference in viscosity measures in the current study.^{2,28} Furthermore, a number of studies have utilized shear rate as a surrogate measurement for shear stress in able-bodied^{29,30} and SCI populations.^{4-6,19} Third, this study includes the use of the oscillatory shear index to provide a simple index of the magnitude of shear reversal. It is likely that vascular endothelium is regulated by a complex interaction of mean shear and oscillatory shear.³¹ Interestingly, in the current study, mean shear and oscillatory shear index are in the direction of an atheroprotective shear profile indicating the likelihood that their interaction would also be atheroprotective. Finally, we did not exclude individuals with cardiovascular or metabolic disease and we did not exclude individuals using medications, caffeine, or tobacco. Instead, we considered that the large number of medications taken by individuals with SCI and the potentially higher rates of other disease would more closely represent the actual medical status of individuals with SCI. Indeed, there was greater medication and tobacco use in individuals with SCI compared to able-bodied individuals and we cannot rule out that their consumption was playing a role in the shear profiles of individuals with SCI. We would assume due to their systemic effects, however, that we would be able to identify differences in the upper-extremity arteries, which was not the case, especially in the carotid artery. These confounding factors interfere with our ability to identify potential mechanisms involved in atherosclerotic processes in lower-extremity arteries of individuals with SCI and a chronic SCI study utilizing an animal model will be necessary to elucidate these mechanisms.

Summary

Results from this investigation suggest that in individuals with SCI, alterations to lower-extremity artery hemodynamics occur in a broad range of SCI levels and completeness. Mean shear and oscillatory shear are important hemodynamic stimuli and alterations to these forces consistently occur in the lower-extremity conduit arteries after SCI. These altered blood flow dynamics appear to be driven by greater antegrade components, and perhaps to a lesser extent driven by smaller retrograde components which serve to increase resting mean shear and to reduce the oscillatory shear index. The combination of these two hemodynamic forces is consistent with an atheroprotective hemodynamic

environment for these lower-extremity arteries. Therefore, future studies investigating peripheral arterial disease in individuals with SCI should focus on alternative mechanisms.

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