Research article

Test–retest reliability of pulse wave velocity in individuals with chronic spinal cord injury

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Background: Pulse wave velocity (PWV), which reflects arterial stiffness, is an important predictor of future coronary artery disease. The test–retest reliability of PWV has not been investigated in people with spinal cord injury (SCI).

Purpose: To report the test–retest (day-to-day) reliability of PWV measurements among people with SCI, and to determine the smallest real difference (SRD) of PWV values.

Participants: Twenty men ($n = 19$) and a woman ($n = 1$) with SCI (C4-T10; AIS A-D; ≥1-year post-injury; 10 with paraplegia and 10 with tetraplegia; time post-injury: 11.8 ± 8.7 years; age: 43.0 ± 12.6 years).

Methods: On two occasions within a 2-week period, aortic PWV (between the common carotid and femoral artery), arm PWV (between the brachial and radial artery), and leg PWV (between femoral and posterior tibial artery) were assessed at the same time of day using Doppler flowmeters.

Results: No statistically significant differences were found between days 1 and 2 in aortic PWV (day 1: 941 ± 185 cm/seconds, day 2: 917 ± 160 cm/seconds, $P = 0.257$), leg PWV (day 1: 1088 ± 141 cm/seconds, day 2: 1122 ± 165 cm/seconds, $P = 0.099$) and arm PWV (day 1: 1283 ± 185 cm/seconds, day 2: 1358 ± 256 cm/seconds, $P = 0.180$). The aortic and leg PWVs had high test–retest reliability (intraclass correlation coefficient: ICC = 0.920 and 0.913, respectively; $P < 0.001$ for both) and arm PWV had moderate test–retest reliability (ICC = 0.598, $P = 0.03$). SRDs for each PWV were 104 cm/seconds (aortic PWV), 97 cm/seconds (leg PWV) and 143 cm/seconds (arm PWV).

Conclusion: The test–retest reliability of PWV assessment is high among patients with chronic SCI. Changes in aortic PWV values above 104 cm/seconds with repeated testing like represent true changes in health status.

Keywords: Spinal cord injuries, Arterial stiffness, Pulse wave velocity, Coronary artery disease, Test–retest reliability

Introduction

Coronary artery disease (CAD) is the leading cause of death among people with chronic spinal cord injury (SCI).[1,2] Individuals with SCI are a specific and vulnerable high-risk population prone to CAD. To prevent CAD morbidity and mortality, it is important to screen for CAD risk factors regularly using noninvasive and reliable methods.

Stiffening of the central or cardiothoracic arteries is identified as a significant independent risk factor for CAD in able-bodied people.[3–5] A decrease in the elastic properties of arteries reduces their buffering capacity, leading to increased pulse pressure, aortic impedance, and left ventricular wall tension, all of which augment the workload of the heart, thereby increasing CAD risk. Several indices have been used to quantify the stiffness of the peripheral and cardiothoracic arteries. These include (1) measuring pulse wave velocity (PWV); (2) relating change in arterial diameter to distending pressure; and (3) assessing arterial pressure waveforms. Of the above methods for measuring arterial stiffness, PWV is the most widely accepted technique and considered as a gold standard measurement of arterial stiffness.[6,7] PWV is the velocity of the blood pressure wave as it travels between two anatomic sites within the arterial system, and is determined dominantly by the elasticity of the artery.[8] The European Societies

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of Hypertension and European Societies of Cardiology have postulated PWV as a representative assessment of arterial stiffness and have indicated common carotid to femoral artery PWV value of greater than 12 m/seconds as indicative of vascular end-organ damage.[9] This indicates people that with common carotid to femoral artery PWV value of greater than 12 m/seconds are at high risk of future CAD. PWV can be measured using several techniques such as tonometers, mechanotransducers, echo-tracking, and Doppler flowmeters. Of the above techniques, Doppler flowmeter is a widely used technique and PWV measured using Doppler flowmeter has been found to be highly reproducible in able-bodied populations.[10,11]

To date, PWV in the SCI population has not been fully investigated, although PWV would be highly valuable in the SCI population.[12] Conventional more invasive methods for early detection of asymptomatic CAD, are often infeasible to administer, difficult to interpret, among individuals with SCI; often precluding them from participation in some forms of diagnostic testing (i.e. graded exercise test for individuals with tetraplegia, Persantine thallium scan). Establishment of a noninvasive diagnostic threshold (cut off value for PWV among individuals with SCI, similar to the 12 m/seconds by the European Guidelines for the general able-bodied population), would contribute to early detection of asymptomatic CAD in people with SCI. Ultimately, the use of PWV measures in the SCI population may identify patients with early disease, to allow for introduction of interventions help to screen for and prevention of arterial stiffness progression prior to the onset of a heart attack or stroke. However, before such evaluations can be made, the test–retest reliability of PWV should be determined in individuals with SCI. In addition, in clinical practice as well as in clinical trials, it is necessary to answer the question of how much difference is due to real change, as opposed to change variation or measurement error, i.e. the smallest real difference (SRD).[13] Thus, the purpose of this study was (1) to report the test–retest (day-to-day) reliability of PWV measurements among people with chronic SCI, and (2) to determine SRD of PWV values in individuals with SCI.

Methods

Subjects

Twenty participants (19 male and 1 female) with chronic (≥1-year post-injury) SCI were included in this study (Table 1). Participants were recruited from an outpatient SCI clinic located at Toronto Rehabilitation Institute, University Health Network, Lyndhurst Centre. All participants were free of signs, symptoms, and history of myocardial infarction, stroke, chronic obstructive pulmonary disease, and diabetes. Three participants were regularly taking medications for hypertension (acetylsalicylic acid, triamterene, and Dyazide); four participants were taking baclofen for spasticity. The study protocol was approved by the Toronto Rehabilitation Institute Research Ethics Board. The participants were given a brief description of the study purpose and then asked to provide written consent for study participation.

Table 1 Subject characteristics ($n = 20$)

Valuables	
Age (years)	43.0 ± 12.6
Level of injury	C4-T10
AIS classification	A–D
Duration of injury (years)	11.8 ± 8.7
Height (cm)	174.7 ± 7.4
Weight (kg)	77.7 ± 18.1

Note: Data are presented as mean ± SD except for level of injury and AIS classification. AIS, American Spinal Injury Association (ASIA) Impairment Scale

Study design

PWV data were obtained from each participant on two separate occasions (days 1 and 2) within a 14-day period. Days 1 and 2 sessions were conducted at the same time of day (approximately 9:00 AM to 1 PM). Participants were at least 12 hours postprandial, having refrained from caffeine, smoking, and heavy exertion for a minimum of 24 hours prior to testing. Medications were not interrupted for data collection; however, medications and dosages were identical on days 1 and 2 for each subject. After a resting period of at least 20 minutes in a quiet and temperature-controlled room, two trained technicians measured PWV. Blood pressure (systolic blood pressure: SBP; diastolic blood pressure: DBP) and heart rate (HR) were measured before and after PWV measurements.

Pulse wave velocity

The same two well-trained technicians did PWV assessments. Two identical transcutaneous Doppler flowmeters (Smartdop50; Hadeco, Inc., Kanagawa, Japan) were used to obtain PWV (1) between the common carotid artery and the femoral artery (aortic PWV), (2) between the femoral and posterior tibial arteries (leg PWV), and (3) between the brachial and radial arteries (arm PWV). The transcutaneous blood flow waves were recorded using a data acquisition system (Power Lab/16SP; AD Instruments, Inc. Bella Vista, Australia) for subsequent off-line analysis. The blood

flow wave was band–pass filtered (2–30 Hz) and the foot of the blood flow wave(the start of sharp systolic upstroke) was identified as the minimum values of the filtered signal. The time difference was identified between the feet of the blood flow waves at the two arterial recording sites. PWV was then calculated as the distance between the two recording sites divided by the identified time, 4, 12, 14–16. The distance between the two recording sites was measured above the surface of body with a nonelastic tape measure. A minimum of 20 simultaneously recorded waveforms were analyzed. The order of PWV measurements (aortic PWV, leg PWV, or arm PWV) was randomized to avoid the possibility of an order or time effect. Brachial SBP and DBP were measured using a mercury sphygmomanometer. Mean blood pressure (MBP) was calculated as DBP + 1/3(SBP–DBP). HR was recorded using an automated HR monitor (UA-767 Digital blood pressure monitor; Omron, Inc., Tokyo, Japan) right before and after PWV measurements.

Statistical analysis

The data are presented as mean ± SD. A paired *t*-test was used to determine significant within-subject differences between days 1 and 2 for each PWV variable. Statistical significance was set at $P < 0.05$ throughout the test.

Intraclass correlation coefficients (ICC) determined test–retest reliability. ICC values were interpreted as poor (0.00–0.20), fair (0.21–0.40), moderate (0.41–0.60), substantial (0.61–0.80), or almost perfect (0.81–1.00).[17] The statistical analyses were performed using IBM SPSS 20 for Macintosh (IBM, NY, USA). In order to assess possible skewness of the PWV data, Bland–Altman plots[18] were provided.

In addition, SRDs were calculated using the equation: $\text{SRD} = 1.96 \times \sqrt{2} \times \text{standard error of measurement}$.[13] The SRD is the smallest threshold required to detect statistically significant change in an individual when taking into account the variability associated with both the measurement technique and experimental sample. In addition, to allow the SRD to be independent of the units of measurements, and thereby used to determine a relative difference after intervention or to detect a relative deterioration over time, the SRD was expressed as a percentage value (SRD percentage).[19] The SRD percentage was calculated by SRD divided by the mean of the measurements from both sessions multiplied by 100%.

Results

One participant could not complete the measurements of leg and arm PWV due to technical difficulty. Thus, the results of leg PWV and arm PWV include 19 participants' data.

There was no statistically significant difference between days 1 and 2 in SBP (day 1: 123.4 ± 17.2 mmHg, day 2: 122.7 ± 19.2 mmHg, $P = 0.830$), DBP (day 1: 82.4 ± 10.9 mmHg, day 2: 82.9 ± 14.8 mmHg, $P = 0.806$), MBP (day 1: 102.9 ± 12.6 mmHg, day 2: 103.4 ± 15.7 mmHg, $P = 0.824$), and HR (day 1: 66.5 ± 8.1 bpm, day 2: 66.4 ± 7.1 bpm, $P = 0.966$). No significant differences were observed between days 1 and 2 for any PWV measures (Table 2). ICC showed high test–retest reliability for aortic PWV and leg PWV (aortic PWV: ICC = 0.920, $P < 0.001$; leg PWV: ICC = 0.913, $P < 0.001$), both of which are categorized as "almost perfect" by Landis and Koch (1977).[17] ICC for arm PWV showed lower reliability (ICC = 0.598, $P = 0.030$), which is categorized as "moderate". There was no correlation between the mean PWV values of days 1 and 2 and the difference between days 1 and 2 in all three PWVs as indicated by the Bland–Altman plot (Fig. 1A–C). Thus, the test–retest reliability of the three PWVs did not appear to depend on the actual values of the measure. The SRD values and the SRD percentages are presented in Table 2.

Discussion

In this study, we evaluated the test–retest reliability of three PWV measurements (aortic PWV, leg PWV, and arm PWV) in people with chronic SCI. We found that

Table 2 Test–retest reliability of aortic, leg, and arm PWV measures

Valuables	Day 1	Day 2	Pa	ICC	SRD	SRD percentage
Aortic PWV (cm/seconds)	941 ± 185	917 ± 160	0.257	0.920**	104	11.2
Leg PWV (cm/seconds)	1088 ± 141	1122 ± 165	0.099	0.913**	97	8.8
Arm PWV (cm/seconds)	1283 ± 185	1358 ± 256	0.180	0.598*	143	10.8

Note: PWV values in days 1 and 2 are presented as mean ± SD.
Pa, based on paired *t*-test.
*$P < 0.05$;
**$P < 0.001$.

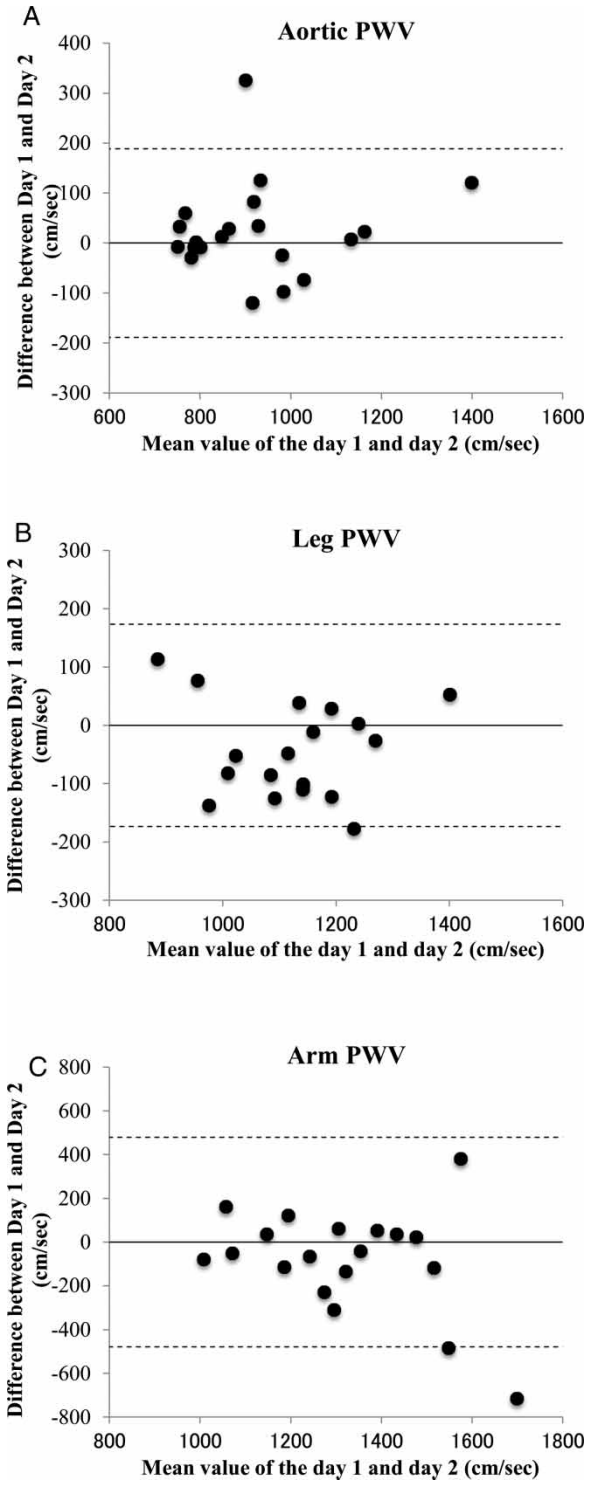

Figure 1 Bland–Altman plot of (A) aortic PWV, (B) leg PWV, and (C) arm PWV. For PWV at each site (aorta, leg, arm), day 1 minus day 2 PWV values are shown on the vertical axis compared with the mean PWV value of days 1 and 2 on the horizontal axis to look for systematic bias. There were no statistically significant correlations between mean values of days 1 and 2, and the differences between days 1 and 2 at any site. The data indicate day 1-to-day 2 reliability were independent from the absolute PWV values obtained. Dashed lines indicate ±2SD.

there were no significant differences between days 1 and 2 for any PWV measures. In addition, aortic PWV and leg PWV had almost perfect test–retest reliability, with ICCs of 0.943 and 0.913 in aortic PWV and leg PWV, respectively, although arm PWV had lower test–retest reliability with an ICC of 0.598. Moreover, the Bland–Altman plot did not show a significant systematic error in any test–retest reliability of PWVs. It is important to emphasize that the most clinically relevant measure, aortic PWV, showed excellent test–retest reliability. Thus, the test–retest reliability of aortic PWV and leg PWV for individuals with SCI is comparable with previously reported test–retest reliabilities in the general population as determined by the use of coefficients of variation,[20] ICC [10,21–23] and Pearson's correlation coefficients.[24,25]

Individuals with SCI may suffer from severe alterations in the autonomic control of the cardiovascular system, as the preganglionic sympathetic fibers that originate in the spinal cord (T1–L2) may be damaged by injury, or simply disconnected from the influence of a higher center. Individuals with mid-thoracic injuries (T6) likely suffer from some loss of adrenergic innervation to the blood vessels of the abdomen and lower limbs, while those with cervical and high thoracic injuries may also have varying degrees of compromised cardiac sympathetic innervation.[26] Studies examining HR variability and blood pressure variability in people with SCI have verified this reduction in sympathetic tone.[27–29] Furthermore, people with SCI above T6 may exhibit a large and sudden increase in blood pressure in response to noxious stimuli below the level of injury; a condition referred to as autonomic dysreflexia (AD). AD is most commonly provoked by bladder distension.[30] Likewise, people with SCI are susceptible to muscle spasticity, which may cause increases in blood pressure and HR. Since short-term change in arterial stiffness is likely mediated by an alteration of vascular muscle tone by systemic factors (e.g. sympathetic nervous activity, circulating hormones)[31] and regional (e.g. endothelium-derived vasoactive substances, exercise muscle-derived metabolites),[32] HR (>120 bpm)[33] or simply by a more distended artery because of increased mean arterial pressure,[34] these SCI-specific conditions may cause variation in PWV. To reduce the effects of SCI-specific conditions on PWV measurements, we had participants rest for 20 minutes in a temperature-controlled room after emptying their bladder and/or leg bag. In addition, no participants were seen to experience muscle spasticity during the aortic and arm PWV testing. Some participants experienced mild lower extremity spasticity during leg

PWV testing. In this scenario, the test was stopped until and restarted after the spasms and clonus had ceased. Although people with SCI are prone to physiological conditions that may periodically disturb sympathetic activity and vary blood pressure, our findings strongly suggest that measures of aortic PWV and leg PWV show acceptable test–retest reliability in people with SCI when proper precautions are taken.

Test–retest reliability for the arm PWV was statistically significant (ICC = 0.589, $P < 0.03$) but lower than aortic and leg PWV. Furthermore, in the Bland–Altman plot the deviation was greater at high arm PWV values (Fig. 1C). A similar deviation (higher PWV values have higher deviation) was reported in able-bodied populations, although it was in the measurements of aortic PWV.[24,35] The reason why the test–retest reliability of arm PWV in our study was lower is unknown. It is unlikely that changes of blood pressure and/or HR affect variations in arm PWV since our results show that there were no differences in blood pressure and HR measurements between the 2 days. In the arm PWV, both propagation time of the pulse wave and the distance between two measurements points are shorter than the other sites (aorta and leg). Consequently, the calculation of PWV is more likely to be affected by measurement error.

The SRD of a test is useful for clinicians and researchers in determining whether the change in PWV values for an individual patient are real, that is, beyond measurement error at the 95% confidence level. In addition, the SRD can be used as a threshold to identify statistically significant individual changes.[36] Our results (Table 2) show that SRDs of the three PWV measurements were 104 cm/seconds (aortic PWV), 97 cm/seconds (leg PWV), and 143 cm/seconds (arm PWV). Thus, if the change between consecutive measurements for an individual patient exceeds the SRD, the individual may be exhibiting significant change. For relative changes, the SRD percentage is independent of the unit of measurement and more easily interpreted. Our results indicated that the size of the relative change (the SRD percentage) should exceed 11.2% (aortic PWV), 8.8 % (leg PWV), and 10.8% (arm PWV) to indicate a real change. For example, the average subject has a 915 cm/seconds aortic PWV and has to decrease by 104 cm/seconds to indicate a real improvement; equivalent values for the lowest and highest subjects are 87 and 160 cm/seconds, respectively.

The exact relationship between PWV and cardiovascular disease among people with SCI is still unknown; however, in able-bodied people, stiffening of the central or cardiothoracic arteries is a significant independent risk factor for CAD.[37–39] It is necessary to determine the relationship between PWV and cardiovascular disease before using PWV as a noninvasive indicator of cardiovascular disease among individuals with SCI.

Conclusion

In conclusion, this study showed that PWV could be used as a repeatable index of arterial stiffness in individuals with chronic SCI if assessments are done under controlled conditions. Given these findings, further investigations should examine the relationship between PWV and cardiovascular disease in people with SCI and verify the psychometric properties of PWV in a larger more representative sample.

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References

1 Frankel HL, Coll JR, Charlifue SW, Whiteneck GG, Gardner BP, Jamous MA, *et al.* Long-term survival in spinal cord injury: a fifty year investigation. Spinal Cord 1998;36(4):266–74.
2 Garshick E, Kelley A, Cohen SA, Garrison A, Tun CG, Gagnon D, *et al.* A prospective assessment of mortality in chronic spinal cord injury. Spinal Cord 2005;43(7):408–16.
3 Boutouyrie P, Tropeano AI, Asmar R, Gautier I, Benetos A, Lacolley P, *et al.* Aortic stiffness is an independent predictor of primary coronary events in hypertensive patients: a longitudinal study. Hypertension 2002;39(1):10–5.
4 Laurent S, Boutouyrie P, Asmar R, Gautier I, Laloux B, Guize L, *et al.* Aortic stiffness is an independent predictor of all-cause and cardiovascular mortality in hypertensive patients. Hypertension 2001;37(5):1236–41.
5 Taquet A, Bonithon-Kopp C, Simon A, Levenson J, Scarabin Y, Malmejac A, *et al.* Relations of cardiovascular risk factors to aortic pulse wave velocity in asymptomatic middle-aged women. Eur J Epidemiol 1993;9(3):298–306.
6 O'Rourke MF, Staessen JA, Vlachopoulos C, Duprez D, Plante GE. Clinical applications of arterial stiffness; definitions and reference values. Am J Hypertens 2002;15(5):426–44.
7 Laurent S, Cockcroft J, Van Bortel L, Boutouyrie P, Giannattasio C, Hayoz D, *et al.* Expert consensus document on arterial stiffness: methodological issues and clinical applications. Eur Heart J 2006; 27(21):2588–605.
8 Oliver JJ, Webb DJ. Noninvasive assessment of arterial stiffness and risk of atherosclerotic events. Arterioscler Thromb Vasc Biol 2003;23(4):554–66.
9 Mancia G, De Backer G, Dominiczak A, Cifkova R, Fagard R, Germano G, *et al.* 2007 Guidelines for the management of arterial hypertension: The Task Force for the Management of Arterial Hypertension of the European Society of Hypertension (ESH) and of the European Society of Cardiology (ESC). Eur Heart J 2007;28(12):1462–536.
10 Sutton-Tyrrell K, Mackey RH, Holubkov R, Vaitkevicius PV, Spurgeon HA, Lakatta EG. Measurement variation of aortic pulse wave velocity in the elderly. Am J Hypertens 2001;14(5 Pt 1):463–8.
11 Calabia J, Torguet P, Garcia M, Garcia I, Martin N, Guasch B, *et al.* Doppler ultrasound in the measurement of pulse wave

velocity: agreement with the Complior method. Cardiovasc Ultrasound 2011;9–13.
12 Miyatani M, Masani K, Oh PI, Miyachi M, Popovic MR, Craven BC. Pulse wave velocity for assessment of arterial stiffness among people with spinal cord injury: a pilot study. J Spinal Cord Med 2009;32(1):72–8.
13 Beckerman H, Roebroeck ME, Lankhorst GJ, Becher JG, Bezemer PD, Verbeek AL. Smallest real difference, a link between reproducibility and responsiveness. Qual Life Res 2001;10(7):571–8.
14 Tanaka H, DeSouza CA, Seals DR. Absence of age-related increase in central arterial stiffness in physically active women. Arterioscler Thromb Vasc Biol. 1998;18(1):127–32.
15 Avolio AP, Chen SG, Wang RP, Zhang CL, Li MF, O'Rourke MF. Effects of aging on changing arterial compliance and left ventricular load in a northern Chinese urban community. Circulation 1983; 68(1):50–8.
16 Sugawara J, Hayashi K, Yokoi T, Tanaka H. Carotid-Femoral Pulse Wave Velocity: Impact of Different Arterial Path Length Measurements. Artery Res 2010;4(1):27–31.
17 Landis JR, Koch GG. The measurement of observer agreement for categorical data. Biometrics 1977;33(1):159–74.
18 Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1986;1(8476):307–10.
19 Flansbjer UB, Holmback AM, Downham D, Patten C, Lexell J. Reliability of gait performance tests in men and women with hemiparesis after stroke. J Rehabil Med 2005;37(2):75–82.
20 Jiang B, Liu B, McNeill KL, Chowienczyk PJ. Measurement of pulse wave velocity using pulse wave Doppler ultrasound: comparison with arterial tonometry. Ultrasound in medicine & biology 2008;34(3):509–12.
21 Casey DP, Beck DT, Braith RW. Progressive resistance training without volume increases does not alter arterial stiffness and aortic wave reflection. Exp Biol Med (Maywood) 2007;232(9): 1228–35.
22 Lehmann ED, Gosling RG, Fatemi-Langroudi B, Taylor MG. Non-invasive Doppler ultrasound technique for the in vivo assessment of aortic compliance. J Biomed Eng 1992;14(3):250–6.
23 Liang YL, Teede H, Kotsopoulos D, Shiel L, Cameron JD, Dart AM, *et al.* Non-invasive measurements of arterial structure and function: repeatability, interrelationships and trial sample size. Clin Sci (Lond) 1998;95(6):669–79.
24 Naidu MU, Reddy BM, Yashmaina S, Patnaik AN, Rani PU. Validity and reproducibility of arterial pulse wave velocity measurement using new device with oscillometric technique: a pilot study. Biomed Eng Online 2005;4–49.
25 Yamashina A, Tomiyama H, Takeda K, Tsuda H, Arai T, Hirose K, *et al.* Validity, reproducibility, and clinical significance of noninvasive brachial-ankle pulse wave velocity measurement. Hypertens Res 2002;25(3):359–64.
26 Strack AM, Sawyer WB, Marubio LM, Loewy AD. Spinal origin of sympathetic preganglionic neurons in the rat. Brain Res 1988; 455(1):187–91.
27 Grimm DR, De Meersman RE, Almenoff PL, Spungen AM, Bauman WA. Sympathovagal balance of the heart in subjects with spinal cord injury. Am J Physiol 1997;272(2 Pt 2):H835–42.
28 Inoue K, Miyake S, Kumashiro M, Ogata H, Ueta T, Akatsu T. Power spectral analysis of blood pressure variability in traumatic quadriplegic humans. Am J Physiol 1991;260(3 Pt 2):H842–7.
29 Wang YH, Huang TS, Lin JL, Hwang JJ, Chan HL, Lai JS, *et al.* Decreased autonomic nervous system activity as assessed by heart rate variability in patients with chronic tetraplegia. Arch Phys Med Rehabil 2000;81(9):1181–4.
30 Karlsson AK. Autonomic dysreflexia. Spinal Cord 1999;37(6): 383–91.
31 Boutouyrie P, Lacolley P, Girerd X, Beck L, Safar M, Laurent S. Sympathetic activation decreases medium-sized arterial compliance in humans. Am J Physiol 1994;267(4 Pt 2):H1368–76.
32 Vanhoutte PM. Endothelium and control of vascular function. State of the Art lecture. Hypertension 1989;13(6 Pt 2):658–67.
33 Callaghan FJ, Babbs CF, Bourland JD, Geddes LA. The relationship between arterial pulse-wave velocity and pulse frequency at different pressures. J Med Eng Technol 1984;8(1):15–8.
34 Nichols WW, McDonald DA, O'Rourke MF. McDonald's blood flow in arteries: theoretical, experimental, and clinical principles Hodder Arnold, London, UK 2005.
35 Lehmann ED, Hopkins KD, Rawesh A, Joseph RC, Kongola K, Coppack SW, *et al.* Relation between number of cardiovascular risk factors/events and noninvasive Doppler ultrasound assessments of aortic compliance. Hypertension 1998;32(3):565–9.
36 Jette AM, Tao W, Norweg A, Haley S. Interpreting rehabilitation outcome measurements. J Rehabil Med 2007;39(8):585–90.
37 Bots ML, Evans GW, Riley WA, Grobbee DE. Carotid intima-media thickness measurements in intervention studies: design options, progression rates, and sample size considerations: a point of view. Stroke 2003;34(12):2985–94.
38 Glasser SP, Arnett DK, McVeigh GE, Finkelstein SM, Bank AJ, Morgan DJ, *et al.* Vascular compliance and cardiovascular disease: a risk factor or a marker? Am J Hypertens 1997;10(10 Pt 1):1175–89.
39 Safar ME, Levy BI, Struijker-Boudier H. Current perspectives on arterial stiffness and pulse pressure in hypertension and cardiovascular diseases. Circulation 2003;107(22):2864–9.