Reliability and consistency of plantarflexor stretch-shortening cycle function using an adapted force sledge apparatus

Short title: Reliability of an adapted force sledge apparatus

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Abstract:
There are various limitations to existing methods of studying plantarflexor stretch-shortening cycle (SSC) function and muscle-tendon unit (MTU) mechanics, predominantly related to measurement validity and reliability. This study utilises an innovative adaptation to a force sledge which isolates the plantarflexors and ankle for analysis. The aim of this study was to determine the sledge loading protocol to be used, most appropriate method of data analysis and measurement reliability in a group of healthy, non-injured subjects. Twenty subjects (11 males, 9 females; age: 23.5 ±2.3 years; height: 1.73 ±0.08 m; mass: 74.2 ±11.3 kg) completed 11 impacts at five different loadings rated on a scale of perceived exertion from 1 to 5, where 5 is a loading that the subject could only complete the 11 impacts using the adapted sledge. Analysis of impacts 4 to 8 or 5 to 7 using loading 2 provided consistent results that were highly reliable (single ICC >0.85, average ICC >0.95) and replicated kinematics found in hopping and running. Results support use of an adapted force sledge apparatus as an ecologically valid, reliable method of investigating plantarflexor SSC function and MTU mechanics in a dynamic controlled environment.

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1. Introduction

The stretch-shortening cycle (SSC) refers to a concentric contraction immediately preceded by an eccentric contraction, with the pre-stretch shown to enhance maximum work output of the muscle in the concentric phase (van Ingen Schenau *et al.*, 1997). It occurs repeatedly in movements like hopping or running (Bosco *et al.*, 1981) which has made it the focus of much research (Comyns *et al.*, 2011; Finni *et al.*, 2000; Geronilla *et al.*, 2003; Ishikawa and Komi, 2004; Regueme *et al.*, 2005; Ishikawa *et al.*, 2006). SSC function is related to both the force and power generated by the muscle and muscle-tendon unit (MTU) mechanics (Kubo *et al.*, 1999). Of particular interest is the measurement of stiffness which refers to the ratio between force and linear or angular displacement. Stiffness can be measured at tissue, joint or limb level and its measurement has become increasingly popular due to its association with both performance and injury. It is believed that an optimal level of stiffness is required to store elastic energy and to absorb impact during landings (Bradshaw *et al.*, 2006). Increased leg and joint stiffness is normally associated with improved performance in power activities (Harrison *et al.*, 2004; Kuitunen *et al.*, 2002; Arampatzis *et al.*, 1999) possibly due to increased muscle cross-sectional area (Ryan *et al.*, 2009) and subsequent increased muscle activation. Excessive stiffness, however, may increase the risk of bony injuries. In contrast, low levels of leg and tendon stiffness are typically associated with increased risk of soft tissue injury (Child *et al.*, 2009; Williams *et al.*, 2004; Arya and Kulig, 2010; Maquirriain, 2012).

The plantarflexors are important in power activities such as sprinting (Bezodis *et al.*, 2008; Johnson and Buckley, 2001) and there is increased reliance upon them with the onset of fatigue (Padua *et al.*, 2006). These muscles and the ankle joint are particularly prone to injury during participation in sport (Fields *et al.*, 2010; van Middelkoop *et al.*, 2008; McManus *et al.*, 2006; Fong *et al.*, 2007). To date, there are few methods that can be used to reliably assess SSC function and MTU mechanics in a controlled yet valid environment.

Studies of *in vivo* plantarflexor SSC function in humans involve dorsiflexion-plantarflexion movements on a force plate (Kubo *et al.*, 2000) or dynamometer (Kubo *et al.*, 2005; Svantesson *et al.*, 1991). The dynamometer improves control but lacks ecological validity for real-life activities such as hopping and running due to differences in kinematics, lack of impact events, unrealistic loading and rate of force development. Oscillation and quick-release techniques are often used to study the mechanical properties of the MTU. The oscillation technique involves modelling the limb as a linear damped-spring system. Oscillations in the force data are measured and input into formulae to determine musculoarticular stiffness. Low levels of perturbation suggest high levels of stiffness, and vice versa (Ditroilo *et al.*, 2011). The quick-release technique measures the stiffness of the series elastic element of the MTU (Goubel and Pertuzon, 1973). This method requires subjects to perform an isometric plantarflexion contraction at a certain percentage of maximal voluntary contraction against a plate which is then suddenly released. Stiffness is calculated as change in joint moment divided by angular displacement (similar to joint stiffness) and related to the isometric torque of the preceding 20 ms with the stiffness-torque relationship considered an index of MTU stiffness. Reliability is established for both methods (Lambertz *et al.*, 2008; McLachlan *et al.*, 2006; Murphy, 2003) with construct validity established for the oscillation technique (Walshe *et al.*, 1996). Neither method provides a measure of the stiffness of the tendon itself however, as measurement of that requires measurement of tendon elongation and tendon force.

Criterion valid methods of investigating MTU mechanics combine ultrasound imaging with isometric dynamometry (Arampatzis *et al.*, 2007; O'Brien *et al.*, 2010; Reeves *et al.*, 2003) or inverse dynamics

(Lichtwark and Wilson, 2005). Construct and criterion validity of the dynamometry method is well-established but content validity of this measure of tendon stiffness is only representative of tendon loaded during isometric contraction. As measures of tendon stiffness are load-rate dependent (Paxton and Baar, 2007), loading during the preceding isometric contraction does not necessarily induce similar tendon behaviour to SSC activities with cyclical eccentric and concentric contractions. The method of Lichtwark and Wilson (2005) requires subjects to hop on a force plate with an ultrasound probe attached to the leg. This method has validity because it measures tendon elongation and force but the reliability of ankle kinematics during a repetitive hopping movement whilst the upper body is free to move can be poor. This is probably due to contributions from other body segments and uncontrolled movement (Joseph *et al.*, 2011). The limitations of methodologies currently used to study plantarflexor SSC function and MTU mechanics, in particular tendon stiffness, suggest a need for a valid (construct, criterion, content and ecological) and reliable method of studying this muscle group.

Force sledges have previously been used to examine SSC function of the entire lower limb (Ishikawa and Komi, 2004; Comyns *et al.*, 2011; Kramer *et al.*, 2010) and allow reliable, controlled measurement in a dynamic environment. A typical lower body force sledge requires the subject to be strapped into a seat as they move up and down on rails positioned at 90° to a fixed force plate at an incline to the ground. This eliminates upper body contribution to lower limb performance, while maintaining a similar movement pattern to hopping or running with a series of impacts. Controlled impact velocity is one reason for improved reliability (Kramer *et al.*, 2010). This is thought to control eccentric muscle loading which can subsequently affect concentric phase performance. Reliability of a lower-body sledge has been previously established for peak force, leg stiffness, flight time and reactive strength index (Flanagan and Harrison, 2007). These variables provide important information about MTU loading and function of the entire lower limb. There are several advantages to using a force sledge for SSC and MTU mechanics studies that involve impacts, but due to the fixed force plate and movable sledge design, the movement of the subject is necessarily large. Therefore, force sledge systems present major difficulties when electromyography data or attachment of an ultrasound probe may be required to obtain addition information on muscle or tendon function.

There are various limitations to existing methods of studying plantarflexor SSC function and MTU mechanics and these are predominantly related to measurement validity and reliability. This study utilises an innovative adaptation to a force sledge which isolates the plantarflexors and ankle for analysis. Subjects are positioned on a plinth at the base of a sledge and a foot contact plate moves up and down the sledge rails. The methodology is advantageous to other sledge protocols as the segment of interest remains in the one place yet the rhythmical loading of hopping and running is still replicated. This allows for the collection of ecologically valid kinematic, ultrasound and electromyography data with minimal noise artefacts. Plantarflexor loading can be increased with the addition of mass to the plate. However, there is a need to examine the reliability and internal consistency of the data produced by the adapted sledge design as a precursor to its use in examining SSC function and MTU mechanics. Therefore, the aim of this study was to determine the sledge loading protocol to be used, most appropriate method of data analysis and measurement reliability in a group of healthy, non-injured subjects.

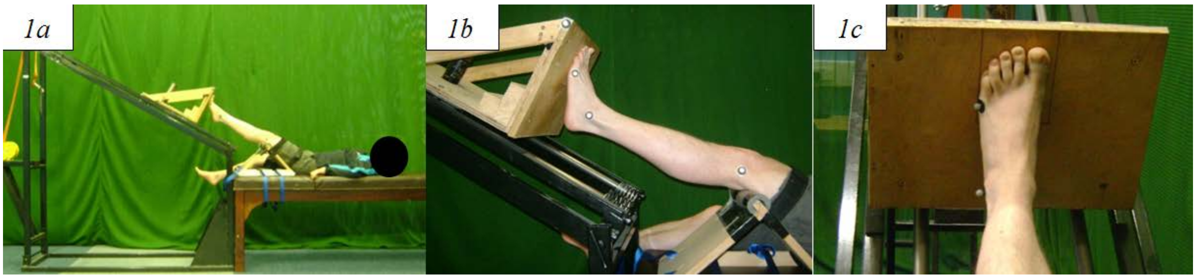
2. Methodology

2.1. Participants

Following university ethics committee approval, twenty subjects (11 males, 9 females, age: 23.5 ±2.3 years, height: 1.73 ±0.08 m, mass: 74.2 ±11.3 kg) gave written informed consent to participate in this study. All subjects were recreationally active, defined as participation in physical activity for at least 30 minutes a day 5 days per week. None had a history of lower limb surgery. They were also injury free in the lower limb for the preceding 3 months.

2.2 Subject preparation

12 mm retro-reflective markers were placed on the sledge plate edge, lateral 5th metatarsophalangeal joint (5MTP), lateral malleolus (MALL) and knee joint centre (KJC) of the dominant legs of subjects. All trials were captured using a six camera 3D motion analysis system (500 Hz, MAC Eagle, Motion Analysis Corporation Inc., Santa Rosa, CA., USA). Subjects were positioned at the base of the sledge as shown in figures 1a, 1b and 1c, and the thigh was secured using Velcro straps. Knee angle was maintained between 150º and 170º and hip angle was approximately 135º. Familiarisation consisted of approximately 25-30 impacts where the subject initially pushed the plate away from them and struck it rhythmically, followed by a second trial where the plate was released from 30 cm and the subject was instructed to strike the plate as rhythmically as possible while minimising plate contact time. There was no mass added to the plate. This protocol was repeated until the subject was satisfied that they were familiar with the task and the researcher deemed the subject was striking the plate as instructed.



Figures 1a-c. *Force sledge set-up. 1a) shows the full sledge set-up with subject secured in place. 1b) shows the motion analysis marker positions on the fifth metatarsophalangeal joint, lateral malleolus and knee joint centre, and 1c) shows the marked area which subjects were instructed to strike as rhythmically and continuously as possible.*

2.3 Test protocol

Testing commenced 5-10 minutes following familiarisation. All trials were completed using the dominant leg which was defined as the preferred hopping leg. The plate began at a position 30 cm above the foot and was released after a '3, 2, 1' countdown. Subjects were instructed (as in familiarisation) to strike the plate in a marked area as rhythmically and continuously as possible for 11 impacts using solely the ankle joint, with the aim of minimising contact time while maximising flight time. Following each trial, the plate was secured away from the foot. Subjects were asked to rate their perceived effort from 1-5 with 1 perceived as very light and 5 maximum exertion where the subject was only able to complete the 11 impacts and no more. Trials were conducted similar to a maximum repetition strength protocol. The objective was to obtain the 11 repetition maximum (11RM) loading in as few efforts as possible with the loading order as randomised as possible. Loadings were determined on the basis of perceived effort rather than absolute mass as no norms or guidelines currently exist for this apparatus. Use of a loading equivalent to a fixed percentage of total body mass was inappropriate due to the localised nature of muscle loading and between-subject differences in plantarflexor muscle mass and strength. Similarly, use of a fixed loading equivalent to a percentage of maximal voluntary contraction obtained using a dynamometer was also considered inappropriate as contractions were not isometric or isokinetic. Average sledge mass at each loading was 12.9 ±2.53 kg (loading 1: 55.9 ±5.9% of 11RM), 15.6 ±2.53 kg (loading 2: 68.2 ±5.3% of 11RM), 18.7 ±3.01 kg (loading 3: 80.2 ±5.2% of 11RM), 20.5 ±3.42 kg (loading 4: 89.3 ±3.7% 11RM) and 23.1 ±3.55 kg (loading 5: 100% 11RM). Subjects were allowed at least 90 s rest between trials but if more time was required this was allowed. If subjects were observed to be excessively moving their knee and contracting their quadriceps they repeated the trial and were reminded to use their ankle to generate force and not the knee. If this continued, testing ceased and the subject was removed from analysis.

2.4. Data treatment

Residual analysis of marker data was performed to find the cut-off frequency which provided the optimal balance between the amount of signal and noise present (Winter, 2005). This was done on a marker-specific basis as the amount of noise in the data changed with marker location. Markers were filtered using a fourth order, zero lag, low-pass Butterworth filter with cut-offs of 12 Hz, 12 Hz, 14 Hz and 18 Hz for the sledge, 5MTP, MALL and KJC markers respectively.

The ankle angle was defined as the angle formed by the 5^{th} MTP, MALL and KJC in the sagittal plane, with 0° defined as an instance where the 5MTP, MALL and KJC were in a line. The angle tended towards 180° when the foot was in dorsiflexion. Ankle angle values were exported directly based on filtered data from motion analysis software (Cortex, Motion Analysis Corporation Inc., Santa Rosa, CA., USA). All other variables were calculated in Microsoft Excel (Microsoft Inc., Redmond, WA., USA).

The plate acceleration was calculated as the second derivative of plate position, with force calculated using Newton's second law. A correction for the component of weight acting down the sledge rails was used since the sledge was inclined at 30°. Plate acceleration in free-fall due to gravity was predicted at 4.903325 $m.s^{-2}$ (i.e. g.sin30°). The effect of friction was determined by calculating the average measured plate acceleration in free-fall across 1500 data points from 10 subjects in all 5 loadings. The difference between the calculated average acceleration and the predicted acceleration at 30° inclination (4.903325 $m.s^{-2}$) was 0.00928 $m.s^{-2}$ (0.189%), therefore friction was assumed negligible in subsequent calculations.

Peak force (F_P) was the maximum force developed during each contact time with rate of peak force development (RPFD) calculated as the peak force divided by the time in seconds it took to reach it. Duration of eccentric loading was defined as the time period it took to reach maximum ankle angle, expressed as a percentage of contact time. Examination of acceleration, velocity and displacement data for the adapted sledge system showed that a precise definition of the first contact "event" was not always clear from the acceleration data alone. In practice, the identification of non-zero acceleration appeared to be the best marker of foot contact on the plate (see figure 2). Therefore, contact time (CT) was defined as the period when plate marker acceleration was greater than zero and flight time (FT) defined as the period when it was zero or less. This is verifiable in comparison to the velocity data which is non-linear during foot contact (figure 2). Plate height (i.e. displacement from release to peak of flight) was calculated using the equations of motion and assumed the periods of upwards and downwards flight were equal. Reactive strength index (RSI) was defined as the ratio between plate height and preceding CT.

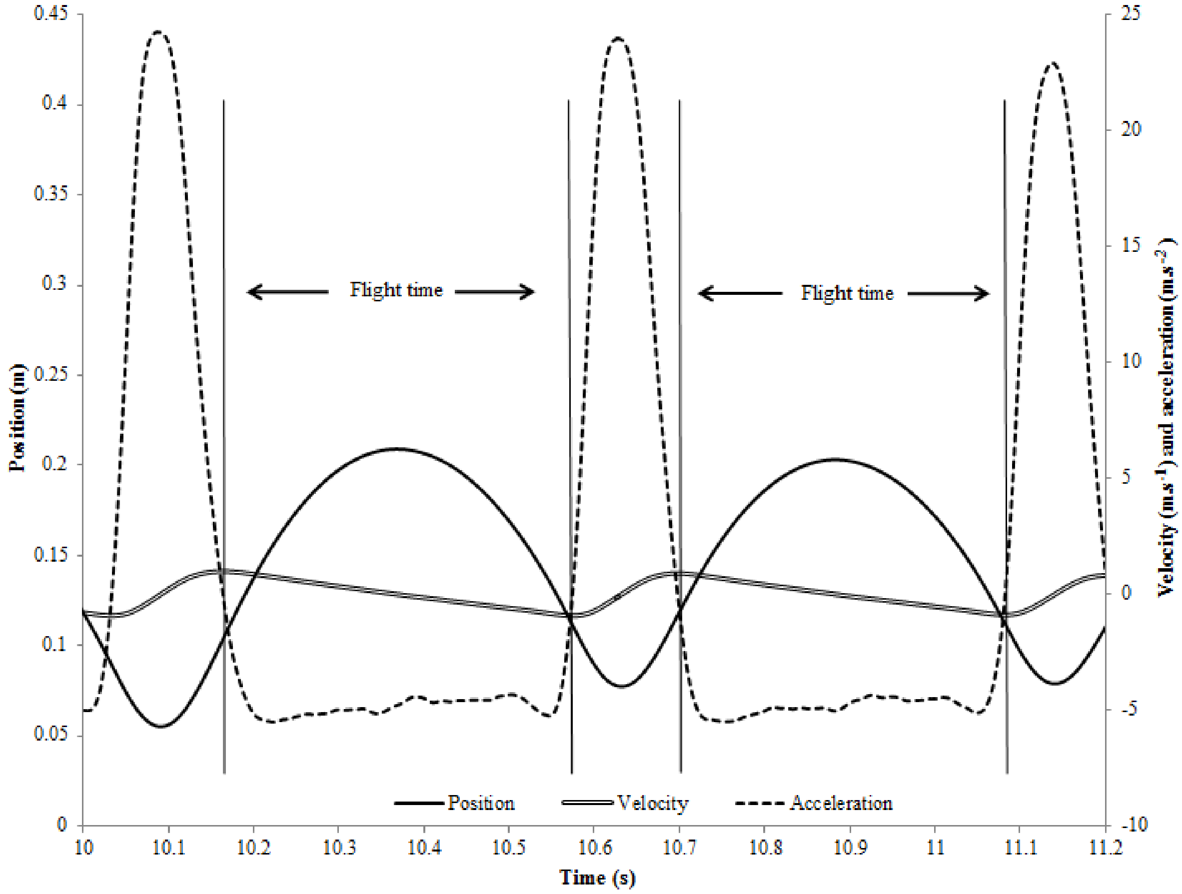


Figure 2. *Calculation of CT and FT based on sledge marker kinematics. CT was defined as the time period when acceleration was greater than 0 m.s^{-2}, and FT as the time between consecutive CT (as shown).*

2.5 Data analysis

Five different analysis strategies were implemented: 1) all impacts included in analysis, 2) impacts 2 to 11, 3) impacts 2 to 10, 4) impacts 4 to 8 and 5) impacts 5 to 7. Pilot work showed that the reliability and consistency of impacts 3 to 5 and 4 to 6 (different combinations of 3 consecutive impacts) were similar to those of impacts 5 to 7, therefore only the results of 5 to 7 are presented here. To account for temporal variation in foot contact times, the ankle angle date were normalised to contact time, with 0% representing the initial contact and 100% representing the release. The within-subject standard deviation was calculated on a point by point basis for all loadings and the five analysis strategies. The average within-subject, point by point standard deviation for all subjects, across the full CT was then calculated for each strategy and loading.

2.6 Statistical analysis

All statistical analysis was completed using SPSS Statistics 19 (IBM, Armonk, NY, USA). The reliability and internal consistency and standardised variation of the variables was determined using single and average intra-class correlations (ICC); using two-way mixed measures with absolute agreement (i.e. reliability), Cronbach's α (i.e. internal consistency) and coefficient of variation (i.e.

standardised variation). The most reliable loading was determined as that which resulted in the combined lowest coefficient of variation (CoV) and highest Cronbach's α and ICC.

3. Results

The results showed that the adapted force sledge provides a reliable method of investigating SSC function of the plantarflexors and the ankle joint complex. Figure 3 shows data from loading 2 and a similar movement pattern was observed at all loadings. Maximum ankle angle was consistent within subjects. The average ankle angle was consistent between impacts for all loadings particularly when the analysis focused on only analysing five or three impacts (figure 3) with a visible reduction in maximum point-by-point SD. When focusing on three impacts rather than all eleven impacts, the range of average point-by-point SD across a trial reduced by between 0.9 and 1.9 degrees for the various loadings. The largest reduction was in loading 2 where the average point by point SD reduced from 4.9 degrees when analysing all impacts to 3.0 degrees when the analysis focused on impacts 5 to 7. Loading 2 also resulted in the lowest SD between impacts (3.0 degrees) with largest SD at loading 3 (3.5 degrees).

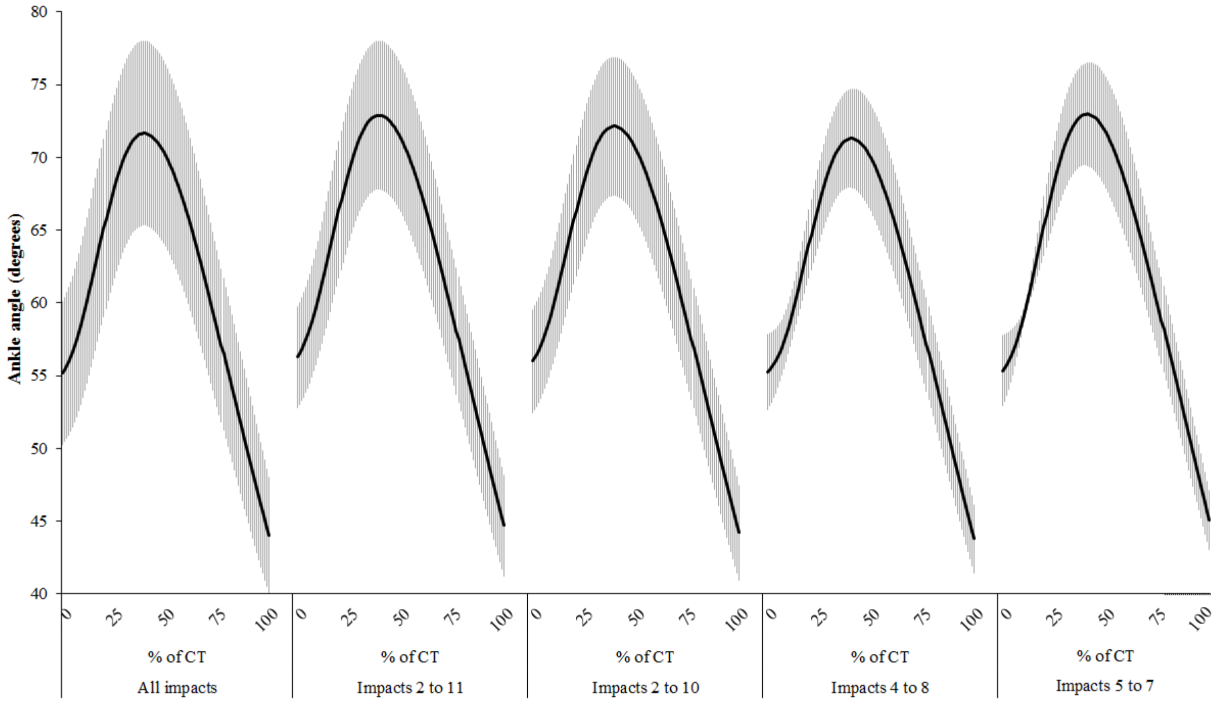


Figure 3. *Ankle angle between-impact consistency over 100% of CT. Solid line indicates average ankle angle over the appropriate number of impacts, grey shading indicates point-by-point standard deviation. Focusing analysis on reduced numbers of impacts reduces standard deviation suggesting this is an appropriate method of reducing time spent on analysis.*

The results were similar for the SSC variables. A reduction in the number of impacts analysed resulted in decreased CoV and increased Cronbach's α and ICC. Depending on variable of interest, the use of a reduced number of impacts for analysis resulted in a reduction in the CoV of 3.6% to 8.8%. Using this concentrated analysis, the Cronbach's α and average ICC for all variables at all loadings was greater than 0.90, suggesting high levels of reliability. Single measure ICC was highest for almost all variables at loading 2. Table 1 shows average, CoV, Cronbach's α and ICC for the variables of interest at the five loadings when the analysis focused on the middle impacts. Of note, the average values obtained were dependent on the loading for F_P, RPFD, CT, FT and RSI.

Table 1. Consistency and reliability for SSC variables at the five loadings during the middle impacts

Variable	Loading	Analysis strategy	Average	Coefficient of variation	Cronbach's α	Intraclass correlation coefficient	
						Single	Average
F_P (N)	1	4 to 8	479.9	5.5	0.99	0.97	0.99
		5 to 7	480.7	5.4	0.99	0.96	0.99
	2	4 to 8	522.0	6.2	0.99	0.97	0.99
		5 to 7	528.1	5.1	0.99	0.98	0.99
	3	4 to 8	558.3	6.7	0.99	0.93	0.99
		5 to 7	558.9	5.6	0.98	0.95	0.98
	4	4 to 8	618.8	5.3	0.99	0.96	0.99
		5 to 7	616.6	5.7	0.98	0.95	0.98
	5	4 to 8	630.4	4.8	0.99	0.96	0.99
		5 to 7	628.6	4.7	0.99	0.96	0.99
RPFD ($N.s^{-1}$)	1	4 to 8	8135.8	9.4	0.99	0.93	0.99
		5 to 7	8170.0	8.8	0.97	0.92	0.97
	2	4 to 8	8169.5	11.3	0.99	0.93	0.99
		5 to 7	8290.0	11.1	0.98	0.93	0.97
	3	4 to 8	8514.4	14.4	0.95	0.79	0.95
		5 to 7	8636.6	13.3	0.92	0.80	0.92
	4	4 to 8	9187.3	15.5	0.95	0.81	0.95
		5 to 7	9087.1	13.9	0.93	0.82	0.93
	5	4 to 8	8887.6	14.4	0.96	0.81	0.96
		5 to 7	8745.0	10.9	0.96	0.88	0.95
Duration of eccentric loading as %CT	1	4 to 8	39.5	8.7	0.95	0.80	0.95
		5 to 7	39.1	8.6	0.91	0.77	0.91
	2	4 to 8	39.6	4.2	0.97	0.87	0.97
		5 to 7	39.8	3.4	0.95	0.87	0.95
	3	4 to 8	38.1	6.1	0.97	0.85	0.97
		5 to 7	38.0	5.7	0.97	0.90	0.97
	4	4 to 8	38.3	6.5	0.96	0.81	0.96
		5 to 7	38.3	5.5	0.96	0.88	0.96
	5	4 to 8	37.6	7.0	0.96	0.83	0.96
		5 to 7	37.6	3.5	0.93	0.82	0.93
CT (s)	1	4 to 8	0.145	5.4	0.97	0.87	0.97
		5 to 7	0.143	4.7	0.96	0.89	0.96
	2	4 to 8	0.161	6.0	0.97	0.87	0.97
		5 to 7	0.159	5.9	0.95	0.85	0.95
	3	4 to 8	0.167	6.6	0.95	0.80	0.95

		5 to 7	0.168	6.2	0.92	0.79	0.92
	4	4 to 8	0.171	7.0	0.95	0.77	0.94
		5 to 7	0.173	5.5	0.92	0.80	0.92
	5	4 to 8	0.179	6.2	0.96	0.83	0.96
		5 to 7	0.177	5.5	0.94	0.84	0.94
FT (s)	1	4 to 8	0.539	5.0	0.98	0.92	0.98
		5 to 7	0.537	4.7	0.97	0.92	0.97
	2	4 to 8	0.535	4.4	0.99	0.96	0.99
		5 to 7	0.537	3.2	0.99	0.98	0.99
	3	4 to 8	0.516	5.5	0.98	0.92	0.98
		5 to 7	0.516	4.1	0.98	0.95	0.98
	4	4 to 8	0.513	5.1	0.98	0.93	0.98
		5 to 7	0.517	4.1	0.98	0.94	0.98
	5	4 to 8	0.502	3.8	0.99	0.95	0.99
		5 to 7	0.502	3.6	0.98	0.95	0.98
RSI	1	4 to 8	1.28	10.3	0.98	0.89	0.98
		5 to 7	1.28	9.8	0.97	0.90	0.97
	2	4 to 8	1.16	9.8	0.99	0.96	0.99
		5 to 7	1.17	7.2	0.99	0.98	0.99
	3	4 to 8	1.02	11.6	0.98	0.91	0.98
		5 to 7	1.02	9.6	0.98	0.95	0.98
	4	4 to 8	0.98	10.4	0.98	0.93	0.98
		5 to 7	0.99	9.1	0.98	0.93	0.98
	5	4 to 8	0.90	8.2	0.99	0.94	0.99
		5 to 7	0.91	7.5	0.98	0.95	0.98

4. Discussion

To our knowledge, this is the first study to use an adapted force sledge apparatus to examine plantarflexor SSC function in a controlled dynamic environment. Flanagan and Harrison (2007) showed the force sledge apparatus which allows for quantification of the entire lower limb's SSC function to be highly reliable with ICC (average measures) of 0.984, 0.987 and 0.989 and ICC (single measures) of 0.953, 0.963 and 0.968 reported for F_P, FT and RSI respectively. The high levels of consistency and reliability found for the adapted sledge apparatus and protocol used in this investigation have important implications for future work, especially in relation to the measurement of MTU mechanics. The sledge protocol of Flanagan and Harrison (2007) allows for study of the entire lower limb as a whole but since the subject is attached to a moving chair, there are large movements of both subjects and equipment. This may result in marker, electromyographic electrode or ultrasound probe movement and data which contain large amounts of noise. The adapted sledge apparatus used in this study ensures that the limb remains relatively stationary and is therefore useful for studies of the plantarflexors that require additional measures of MTU function. The isolation of the limb allows markers, electrodes or probes to be attached to the limb with minimal chance of movement thereby ensuring low noise signals. The results show low variability and high reliability of forces, RPFD and duration of eccentric loading, all of which may affect the measurement of MTU mechanics. The low levels of variability allow accurate detection of small changes over a period of time. This enhances the experimental sensitivity which can be important in experimental designs such as training interventions where changes over time may be quite small. This study used three-dimensional motion analysis which is considered the gold standard for marker kinematics to study the plate and ankle during cyclical loading. A potentially acceptable alternative to this methodology could involve the use of an accelerometer attached to the plate to measure acceleration and electrogoniometers attached to the ankle to measure ankle angles.

It is desirable to focus analysis on the middle impacts due to the hugely reduced point-by-point SD of the ankle kinematics, suggesting increased movement consistency. CoV of the SSC variables also decreased when the analysis focused on these particular impacts. Cronbach's α remained correspondingly high as did both single and average ICC suggesting this is an efficient analysis protocol for use with large subject numbers. In studies of tendon stiffness, the measurement of tendon elongation requires time consuming manual digitisation of tendon ultrasound images. It is hence desirable to try to reduce the amount of data analysed while maintaining reasonable sample size and high reliability and consistency. Large decreases in the CoV were observed when the first and last impacts were removed from analysis, which is not surprising as the first impact is not part of the cyclical loading pattern. The last impact may be subject to cumulative fatigue or lack of concentration. The analysis strategies focusing on the middle impacts were more reliable as the subject was in working in a consistent rhythm. These results are similar to Flanagan and Harrison (2007) who found measurement reliability during a rebound protocol to be higher than during a single drop jump due to the rhythmical nature of the impacts. Use of the middle impacts also allows for tendon conditioning to occur before images are extracted for analysis, which is essential for accurate reliable measurement of tendon elongation and hence stiffness (Magnusson *et al.*, 2008; Maganaris, 2003). As subjects must undergo protocol familiarisation prior to testing, the tendon should have experienced enough conditioning prior to testing to ensure reliable measurement.

All loadings were reliable but use of loading 2 typically resulted in the highest single trial ICC and CoV scores. This loading resulted in good (ICC >0.85) to excellent (ICC >0.95) reliability for single and average measures. Additionally, the subjects generally described this loading as being of low difficulty to complete 11 impacts. The use of heavier perceived loadings, particularly for a muscle group which rarely works in isolation, could result in early subject fatigue which is known to affect joint kinematics and kinetics (Kellis and Liassou, 2009; Sanderson and Black, 2003). The high levels of consistency within loading supports the use of a scale of perceived exertion as an appropriate method of determining sledge loading. The changes in average values obtained for F_P, RPFD, CT, FT and RSI must be considered in designing appropriate test protocols and prior to analyses, suggesting similar loadings must be used for comparison.

This is the first study to produce statistics to support the use of an adapted force sledge to increase control of the duration of eccentric loading on a muscle group or limb. The results show acceptably low standardised variability scores (CoV); high internal consistency (Cronbach's α) and high reliability (ICC). Across all loadings, the average duration of eccentric loading was consistently between 38 and 40% of CT, suggesting that sledge load was not a factor that affects phase duration. This is most likely because of the restriction of sledge and limb movement to one plane. The duration of eccentric loading is of particular interest in SSC studies, as researchers may wish to examine how manipulation of the eccentric phase affects subsequent concentric performance. Controlled loading is also beneficial in training studies which consider the effectiveness of eccentric training on MTU mechanics.

The methodology used in this study provided cyclical loading of the lower limb which is similar in contact times to real-life activities such as running and hopping (Babić *et al.*, 2011; Hayes and Caplan, 2012). The ankle joint kinematics and SDs using the sledge were also similar to those reported in other studies (Mero and Komi, 1985; Jacobs and van Ingen Schenau, 1992; Hunter *et al.*, 2005). The aim of this study was to determine the sledge loading protocol, most appropriate method of data analysis and measurement reliability in a group of healthy, non-injured subjects for the application of the adapted sledge system. For simulation of cyclical loading patterns similar to hopping or running, the use of a subjective loading of 2 on a scale of perceived exertion ranging from 1 to 5 and analysis of the middle (4 to 8 or 5 to 7) impacts provided consistent results that were highly reliable. In conclusion, the results show this apparatus is suitable for investigating plantarflexor SSC function and MTU mechanics in a dynamic controlled environment.

5. Acknowledgements

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