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THE EFFECT OF STRENGTH AND ABSOLUTE LOAD ON POSITION VARIABILITY IN ISOMETRIC POSITION TASKS

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ABSTRACT

The purpose of this study was to investigate the relationship between strength and position control, with an emphasis on measurements at low, absolute levels of force, as well as to examine the effect of load on position control. 33 healthy and physically active male university students were subjected to maximum voluntary contraction (MVC) tests and a weighted positional knee extension task involving trials at force levels ranging from 0.5-20kg, with the goal of maintaining position. Among the principal findings was the fact that strength did not affect position variability at lower levels of force, while at higher force levels, the stronger subjects exhibited lower levels of position variability. Thus, it was concluded that general strength training up to a certain level is non-detrimental to force control at low levels of resistance, and that increases in strength may contribute positively to force control at moderate force levels. In accordance with previous research, variability increased as a function of load, while variability relative to load decreased with added weight. At the heaviest weights, strength became the main determinant of performance, while its importance at lower force levels was negligible. Mean and maximum frequency of velocity and acceleration exhibited a U-shaped relationship with weight, which at the lower end was attributed in part to an inability to perceive and correct for the small force oscillations, as well as low inertia.

INTRODUCTION

The term force control denotes the ability to grade force according to a target level. Muscle force is graded through the activation of motor units, which fraction muscles into independently controllable units, allowing for asynchronous activation of the different units. Motor units are recruited in an ascending manner according to size (Henneman, 1957), and the contraction of associated fibers is controlled through motor unit firing modulation. Hence, the precision of force output is in large determined by the ability to modulate motor unit firing and activate a suitable number of motor units, as well as the characteristics of the latter.

A certain level of force variability is present in all contractions. Signal-dependent variability is largely agreed to result mostly from fluctuations in motor unit firing and recruitment (Jones, Hamilton & Wolpert, 2002; Taylor, Christou & Enoka, 2003). It has been described both as a linear increase with force across part of the force range (Galganski, Fuglevand & Enoka, 1993; Hamilton, Jones & Wolpert, 2002; Smits-Engelsman, Smits, Oomen & Duysens, 2008; Krishnan, Allen & Williams, 2011), as exponential (Slifkin & Newell, 1999), as well as sigmoidal (Christou et al., 2002) across the entire force range. However, greater variability relative to force is typically seen at the upper and lower end of a subject’s force range (Galganski et al., 1993; Laidlaw, D.H., Kornatz, K.W., Keen, D.A., Suzuki, S., & Enoka, R.M., 1999; Christou, E.A., Grossman, M., & Carlton, L.G., 2002; Taylor, A. M., Christou, E. A., & Enoka, R. M., 2003). Taylor et al (2003) reported that the minimum coefficient of variation (CV) for force was found at approximately 30% MVC, and stated that CV was seen to decline from a maximum at 2% MVC to a minimum at 30% MVC, to increase to a plateau that started at 50% MVC. This is further supported by the findings of Laidlaw et al (1999), who found that while the standard deviation of force fluctuations increased linearly as a function of force for all subjects between 2.5-20% of MVC, CV of force decreased. Cited by Taylor et al (2003), Burnett, Laidlaw and Enoka (2000) found that CV for force declined to 20% MVC and increased at 50 and 75% MVC. Christou et al. (2002) theorized that while recruitment of smaller motor units may constitute the main mode of force gradation at lower force levels, firing rate modulation takes on increasing significance at higher levels. A similar explanation for the observed U-shape in the relationship between force level and relative variability has been proposed by Slifkin, Vaillancourt and Newell (2000). "In the 30-40% MVC region of the potential range of force output, both force gradation strategies, recruitment and increased firing-range modulation may operate. […] The possibility of engaging one or both principles of force gradation in the 30-40% region reflects greater flexibility (degrees of freedom) in the adaptation of force output to the force target. In contrast, as the force requirement diverged from that level, adaptation was increasingly restricted to the engagement of a single gradation strategy; that is, motor unit recruitment was engaged at lower force levels and rate modulation was engaged at higher force levels" (Slifkin & Newell, 2000, p. 150). Thus, the magnitude of the relative force variability seen at low force levels is largely due to the small number of active motor units and the resultant impact of recruitment or de-recruitment, as well as the "proportionally […] greater effect on force output" from firing rate fluctuations (Sosnoff & Newell, 2006, p. 87) or motor unit synchronisation (Yao, Fuglevand, & Enoka, 2000).

Changes in muscle morphology are evident in strength trained individuals. Different modes of training evoke somewhat different responses and define the magnitude of the different effects, but some general trends can be discerned. Although a greater hypertrophic response is generally seen in type II fibers as opposed to type I fibers, increases in physiological cross-sectional area is evident throughout the whole fiber range in response to strength training (Kremer et al., 1995; McCall et al., 1996; McCarthy et al., 2002; Putmann et al., 2004). A number of studies also report changes in muscle fiber characteristics, most commonly in the direction of IIx to IIa (Andersen & Aagaard, 2000). Other possible alterations include but are not limited to changes in the ratio of non-contractile and collagenous proteins to contractile proteins, increases in fascicular length and increases in pennation angle, and possibly hyperplasia. Most importantly, both hypertrophy and hyperplasia result in larger and potentially stronger motor units, through increase in amount of contractile elements and/or increased sarcoplasmic volume, and proliferation of cells, respectively.

Christou, Grossman & Carlton (2002) found that force variability was most closely connected to the percentage of MVC at which one is operating, and no significant differences in variability at %MVC have to this author's knowledge been found between controls and strength trained subjects, or following periods of training (Keen et al., 1994; Smits-

Engelsman et al., 2008; Beck et al., 2011; Panjan et al., n.d.). The seeming lack of change in variability at relative force levels (%MVC) logically implies an absolute expansion of the relative variability curve in stronger subjects. Thus, we theorized that the previously described lower zone of increased relative variability would encompass a larger segment of the absolute strength span of stronger subjects.

The “amplitude of […] force fluctuations will increase as more large motor units are recruited” (Smits-Engelsman et al., 2008, p. 59), and therefore a general enlargement of motor units, as is often seen with strength training, could reasonably be expected to cause lessened force steadiness. The amount of force exerted by a muscle is ultimately dependent on motor unit activation and firing patterns, and by increasing the size and (potential) strength of the smallest muscle fibers, resolution of force (smallest achievable adjustment) could be decreased. In fact, for enlarged motor units not to lead to alterations in steadiness, some form of compensation must take place, as larger motor units are bound to decrease force accuracy without. It is therefore possible that stronger subjects, in which even the smallest motor units have been enlarged and strengthened, could experience an increase in the absolute (not relative) size of their lower end zone of force variability. A longer range of low level force variability in absolute terms could have a great number of implications in daily life.

While it was stated by Sosnoff & Newell (2006, p.86) that ”the use of absolute force targets [in a study] will result in weaker subjects producing force at greater relative force levels and consequently artificially increasing the differences in the absolute level of force on which variability is assessed”, this view is not shared by this author. The weight of a coffee cup remains relatively constant, and nearly all tasks involving the physical movement of objects involve objects of non-changing mass. In short, everyday life, as well as sport, force generation seldom scales according to an individual’s strength, and, with purely practical implications in mind, relative measurements would therefore be of a somewhat limited value as opposed to investigating the possibility of strength-based differences on force variability at absolute force levels.

Strength training has previously been shown to affect force control in a number of different populations. However, while studies on elderly, impaired and untrained subjects show reduced force fluctuations with training and subsequent increases in strength (e.g. Keen et al., 1994; Beck et al., 2011; Laidlaw et al., 1999; Bilodeau et al., 2000), data on stronger populations is somewhat sparse. In previous studies, subjects labeled as strength trained and healthy controls have not been shown to differ in force steadiness in tasks measuring "the ability to control forces with the [flexor] muscles of [the] index finger" (Smits-Engelsman et al., 2008), force steadiness in "isometric knee extensions" and "three 60-second repetitions of dynamic active torque tracking task" (Panjan et al., n.d.), and "force steadiness and common drive for the vastus lateralis muscle" (Beck et al., 2011). However, some inherent limitations in these studies seem to justify further inquiry into the matter.

Keen et al. (1994) and Beck et al. (2011) put subjects through 12 and 8 week training programs. It is quite established that initial strength gains often precede significant muscular growth (Enoka, 1997), and even though some hypertrophy was confirmed to have occurred in the target musculature in Keen et al.'s (1994) study, 2-3 months is too short a time for considerable hypertrophy to occur. At least at the scale probably needed to illicit major alterations in the accuracy of force gradation. Furthermore, Smits-Engelsman et al. (2008), Keen et al., (1994), and Beck et al. (2011) all measured variability at set percentages of their subjects' MVCs. While Smits-Engelsman et al. (2008) scaled standard deviations relative to the actual generated force and found that strength trained subjects seemingly exhibited lower variability at higher force levels than controls, the lack of absolute measurements leaves for an incomplete picture. In addition, while data exists on variability at low force levels in for instance isometric index finger abduction (Keen, Yue, & Enoka, 1994; Sosnoff, Valantine, & Newell, 2006), studies on force control in healthy subjects employing the quadriceps musculature have typically not included measurements at levels below 5% of MVC (Winter & Challis, n.d.; Schiffman & Luchies, 2001; Christou, Grossman & Carlton, 2002; Schiffman, Luchies, Richards & Zebas, 2002 ; Smits-Engelsman et al, 2008; Beck et al., 2011).

The frequency content of force signals has not been examined to the same extent as amount of variability in force control studies (Sosnoff, Valantine, & Newell, 2006), but the frequency structure of force output has been found to "not change in the same direction as do changes in the magnitude of variability" (Slifkin & Newell, 1999, p. 840). The frequency content of force- or positional signals offer some insight into the employment of control strategies, and Smits-Engelsman et al. (2008) found that strength trained subjects exhibited more power in the 1-6Hz band than controls, which was taken to indicate greater use of longer feedback loops, as well as the strength trained subjects using “a more somatosensory (5-6Hz) feedback controlled strategy” (p.65).

The majority of the literature on force control has investigated force variability in isometric force production tasks. However, position variability in a weighted positional task can also serve as a measure of force variability, as failure to produce the precise force required to counteract an external pull and maintain position results in movement. Thus, isometric position tasks can be employed to examine the characteristics of force output, as long as one takes into consideration the factor of inertia, as well as the difference in control strategy and feedback utilization due to the characteristics of the task.

The purpose of this study was to further investigate the relationship between strength and position control, with an emphasis on measurements at low, absolute levels of force, as well as to examine the effect of load on this control. This was done by analyzing the variability and frequency content of positional signals.

METHODS

Participants

	Mean	St deviation
Age	22,3	2,1
Height (cm)	181,5	7,4
Weight (kg)	82,9	10,5
Thigh Circumf. (cm)	58,0	5,3
Lower leg length (cm)	38,6	2,7

Table 1: Participants

The subject group comprised 33 healthy (self-reported) male university students between the ages of 19 and 27 years. It was preferable for subjects to be at the least nested within what could be defined as a normal, healthy range with regards to strength, so as not to mask any potential difference in force variability between the average and the stronger subjects. In order to be eligible for participation, subjects were therefore required to perform at the least some form of lower body strength training at a regular basis and/or participate in a sport that taxed the lower body to a certain extent. Inactivity and resulting weakness do not constitute normal human traits. Several had multiyear backgrounds from varying forms of strength training. Subjects were asked to abstain from training their legs the 48 hours prior to testing.

In this study, we employed male subjects only. Females in general are far from possessing the same potential for muscular growth and strength increases as their male counterparts, and were therefore deemed less than optimal as subjects for the present study, in which strength and hypertrophy are key elements. Certain studies also point to gender differences with regards to force control (Clark, Collier, Manini & Ploutz-Snyder, 2005; Brown, Edwards & Jakobi, 2010; Brown, 2011).

The subjects' height and weight was measured, as well as thigh circumference below the gluteal fold and the distance between caput fibulae and lateral malleus in the dominant leg. We deemed it probable that stronger subjects would on average also exhibit greater quadriceps PCSA, and thigh measurements were done in the hope of it being able to serve as an indicator of thigh muscularity.

Testing Modalities and Procedure

A positional knee extension task was chosen as the mode of measurement. The relative simplicity of the task was thought to ensure that the stronger and more strength trained individuals were no overly favoured in terms other than strength, while simultaneously allowing for the expression of markedly dissimilar levels of strength in the group.

The positional task involved the subjects being seated in a chair that had been heightened somewhat, ensuring that the lower leg could move freely without touching the bench on which the chair was mounted. A pulley system was located 6.3 meters behind the chair and bench, consisting of a light-weight bicycle wheel mounted on the wall, providing minimal friction. Due to it being very light and inelastic, kevlar wire was used to transfer force from weight plates under the pulley system and to the subject’s ankle. The kevlar wire formed a negligible <3 degree angle with the floor at the subject’s ankle. A separate steel wire with a force cell attached was fastened to the wall and used for measuring maximal voluntary contractions (MVC). Pictures 1-3 display part of the setup.

Subjects were seated facing away from the pulley, with lower legs hanging from the edge of the chair. When participants were asked to let their dominant leg hang passively, an angle of around 90 degrees formed between femur and tibia, and this position was used as reference for the positional tasks, as well as for measuring isometric MVCs. The vertical positioning of the shin removed neutralized inertia.

Two MVCs were performed; one at the beginning of and one at the end of the testing procedure. Subjects were instructed to produce as much force as possible in the ten second measuring window, while avoiding changes in hip angle, so as to prevent the utilization of the body as a fulcrum. These tests were isometric, executed with the lower limb in the reference position, and the best result obtained by each subject was subsequently used in analysis. We chose to allow for two attempts to ensure that subjects were able to properly display their strength, and opted for placing the tests at the start and beginning of the procedure to minimize fatigue. Subjects did not perform warm ups before the tests, in part due to increasing temperature above resting levels having been shown to have very little effect on isometric force production (Bishop, 2003).

The positional tasks required that the subjects exerted knee extension force against the posterior pull provided by the wire and its attached weight in an effort to keep the lower leg in the aforementioned reference position. The subjects were told to keep their leg as still as possible, and were allowed to hold on to the sides of the chair during testing, if they felt it helped prevent shifting. The participants were able to see their foot, and were left to decide for themselves if they wished to look at it during testing. Two ten second trials were done at 0.5, 1.25, 2.5, 5, 10, 15, 20 and 1.25 kg again, followed by a final MVC. The last to trials at 1.25kg were done to check for fatigue. The subjects were given control of the load by the help of an assistant positioned at the pulley, which held and then gradually let go of the weight. Measurements started once the subject appeared to have full control over holding the weight, and any initial transitional movements had subsided. All subjects managed to control the weight at all levels for the entirety of the measurements. Subjects rested a minimum of 1 minute between trials, and were allowed to decide for themselves when they felt ready to start each test. As for the reference position, subjects were told to try and hold it, but no feedback or comments were given during trials. Participants were, however, shown approximately where to put their foot at the start of each new trial, if they were thought to demonstrate excessive flexion or extension.

Tests at percentages of MVCs were omitted in favour of measurements at absolute levels of force. The weight range was selected with the primary aim of subjecting the participants to tests at low levels of force to attempt to determine the possible effect of hypertrophied type I fibers on force variability, as well as including higher force levels to allow the subjects to demonstrate what was theorized to be better relative control at these weights, i.e. produce force above the lower zone of decreased relative stability. The testing order was not randomized, as we deemed it possible for trials at the heavier weights to affect subsequent performance.

Instrumentation

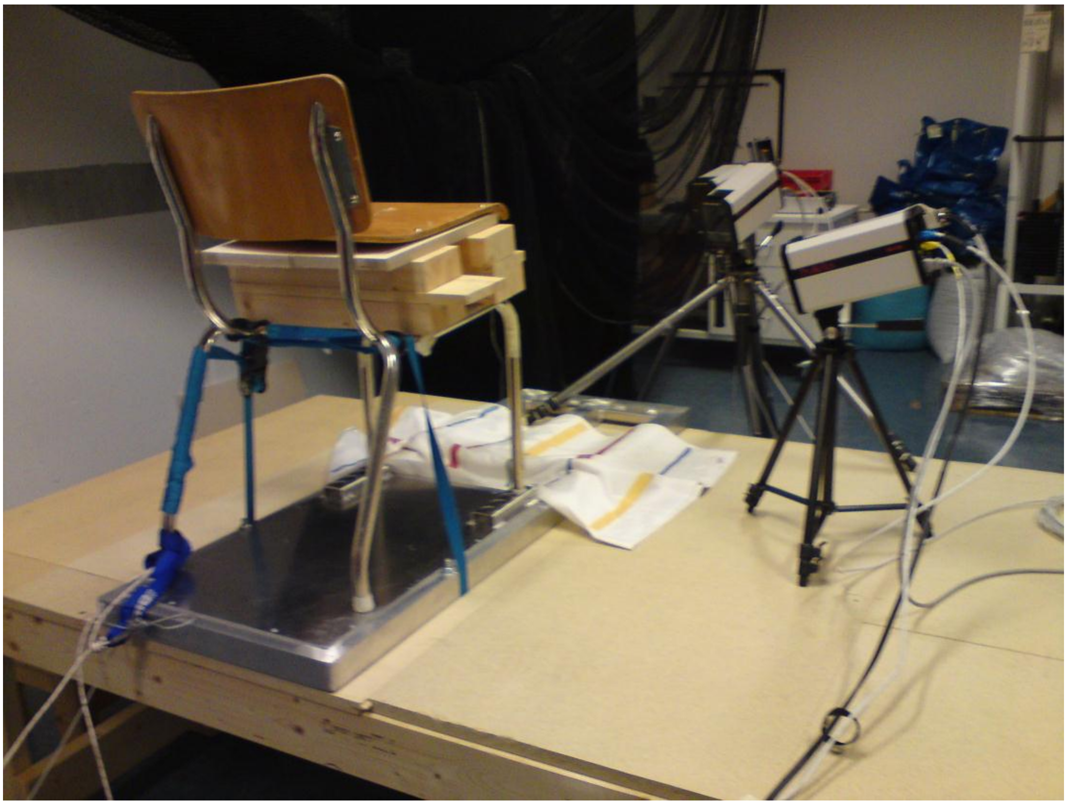
Three ProReflex MCU 500 motion capture cameras arranged in a quarter circle gathered positional data at 500Hz from a reflex marker on the front of the shin of the dominant leg, placed one quarter of the distance between caput fibulae and lateral malleus above the latter. Stationary recordings showed a noise band less than 0.00Xmm on average. An Interface SML-500 force sensor capable of measuring up to 226 kilograms of force was used for MVC-tests, and a DTS inclinometer and accelerometer were fastened to the shin to either side of the reflex marker to provide data from the positional tasks which would allow for validation of the data provided by the cameras. Data from the latter two are not further reported in this thesis.

Analysis

All force and positional data were captured using Qualisys Track Manager, and later exported to matlab. When analysing the data, positional changes were measured as movement in the sagittal plane. 14 variables were derived from the positional signal for each trial; mean position, drift, standard deviation of position, velocity and acceleration, as well as maximum, mean and median frequency of position, velocity and acceleration. Standard deviation was chosen as the measure of variability due to it not being very sensitive to spikes, and because it has been used in a majority of force control studies, giving further room for comparison of results.The first second of the data from each trial was removed to ensure no transitional movements were included, and the mean result of each pair of trials was used. Velocity and acceleration were derived from position with a differentiating filter, and frequency from fast fourier transform. A 15Hz low-pass filter was used to remove signal noise. Drift, i.e. a continuous transient movement (0Hz) of the leg, was calculated as the mean slope of the position trace in time. This drift was removed from the signal before all other variables were derived. Linear interpolation was utilized in the very rare occurrence of missing data. Pearson's correlation coefficient was used to determine correlation strength.


Picture 1: The pulley system

Picture 2: Frontal view of chair and motion capture cameras, with pulley visible in the background



Picture 3: Chair and motion capture cameras

RESULTS

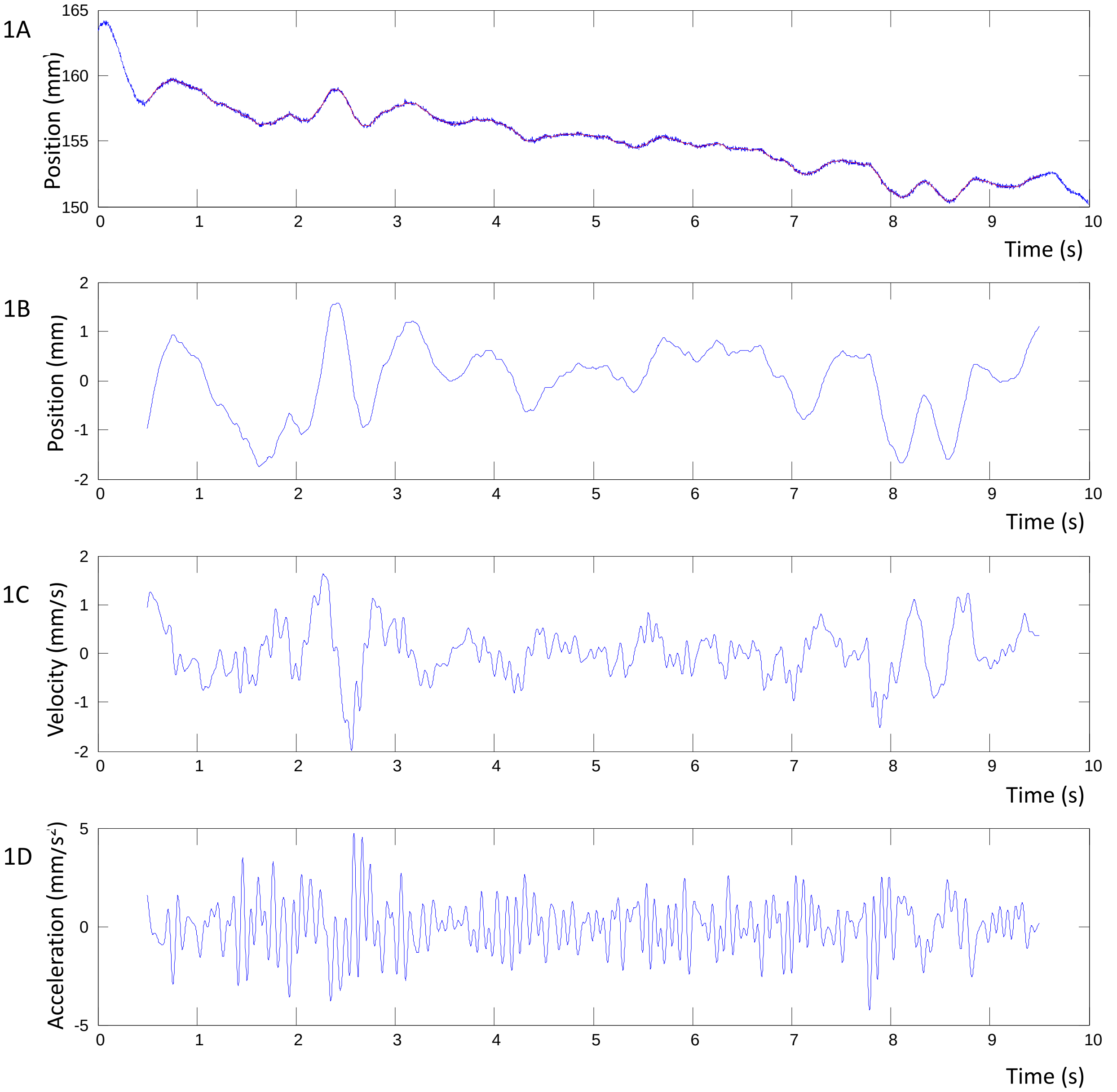


Figure 1 A.:Position time trace of horizontal backward-forward movement, both raw (blue) and filtered (red). B: Detrended position time trace. C: Velocity, i.e. time derivative of detrended position trace. D: Acceleration of the same signal.

Figures 1A-D show part of the analysis process. Figure 1A depicts a raw and filtered position signal, while figure 1B shows the same filtered position signal after it has been detrended to remove drift before further analysis. The velocity and acceleration signals derived from the position signal are shown in figures 3 and 4.

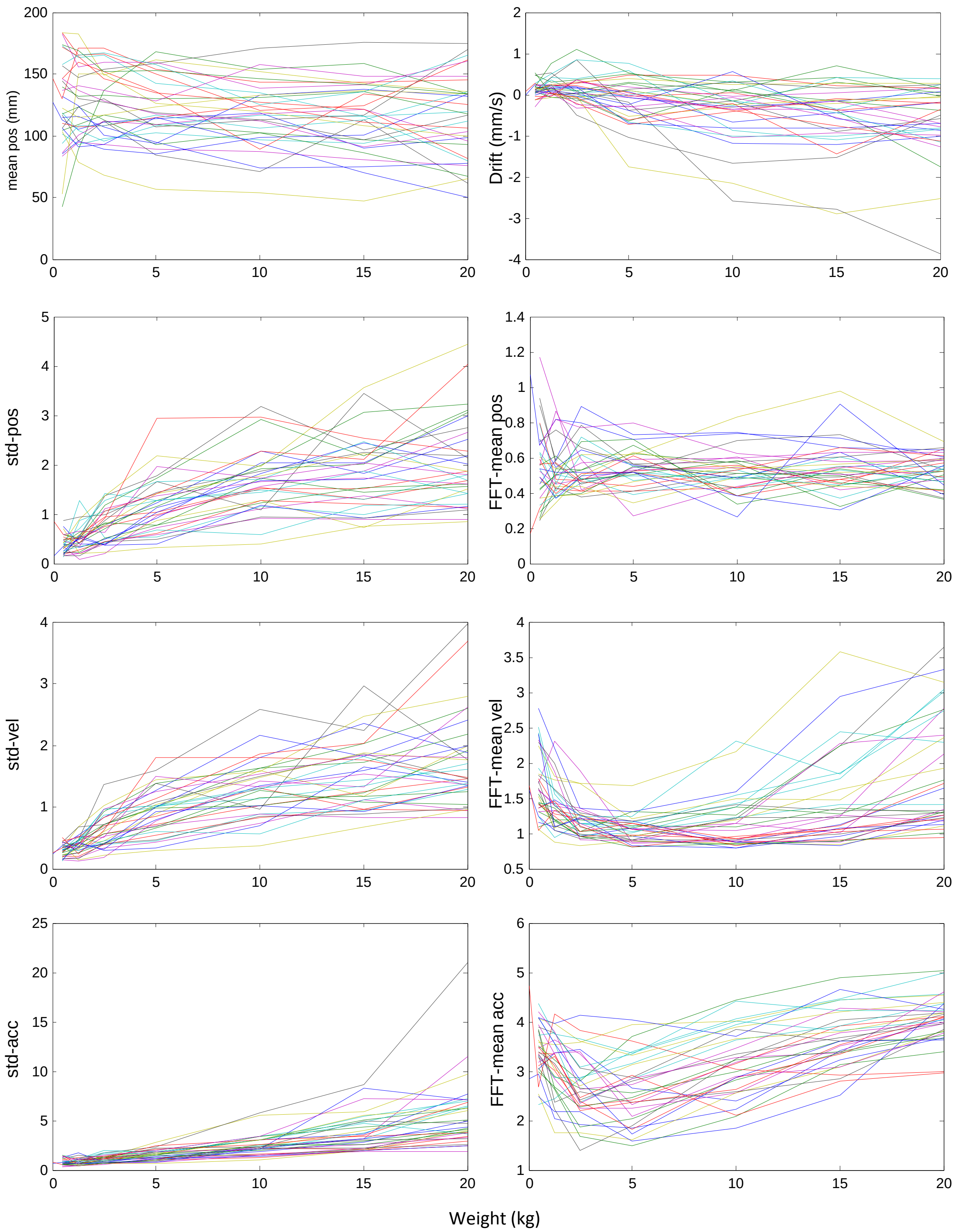


Figure 2: Performance of all subjects across the weight Span

Figure 2 shows the values of each individual subject across all force levels for mean position, drift, standard deviation of position, velocity and acceleration, and mean frequency of position, velocity and acceleration. This offers a glimpse into the data material from which a substantial portion of the results presented in this section were derived.

Strength and variability

As can be seen in table 2, the subjects' best results in the MVC tests averaged 67.25kg, with a standard deviation of 18.08. Figure 3 shows the distribution of strength among the subjects, with a large portion of the participants centered around the mean and median values. Results from the first MVC-test were highly correlated with subsequent performance in the second (R. 0.854, $P<0.01$). A paired samples t-test revealed a non-significant 3,44kg (P: 0.085) difference between mean performance in favour of the last MVC-test. For the group as a whole (N=33), no significant ($P<0.05$) relation was found between strength and force control. Across all levels of resistance as a whole, P-values were insignificant for mean position, drift (in time), and standard deviations of position, velocity and acceleration, and maximum, mean and median frequency of the position, velocity and acceleration signals.

Some tendencies, while not statistically significant at the $P<0.05$-level, were observed with regard to mean position, and standard deviation of position and velocity in particular. For instance, the correlations between MVC and mean position at 15 and 20 kilograms of resistance yielded R-values of 0.32 and 0.26, with corresponding P-values of 0.19 and 0.14. Standard deviations for position were also interesting with p-values of 0.11, 0.15 and 0.10 at 5, 10 and 20kg.

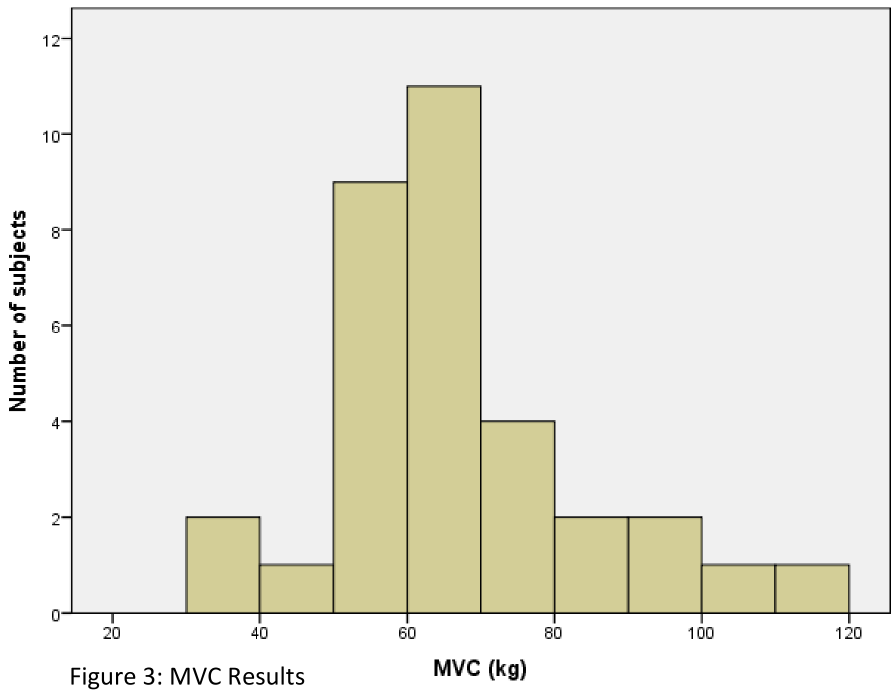


Figure 3: MVC Results

N	Min	Max	Mean	Median	St dev	Range
33	30.20	117.30	67.24	64.30	18.08	87.10

Table 2: MVC Results

However, these results may be somewhat misleading due to the distribution of strength in the subject group. The strongest subject may be considered an outlier with regard to strength, and analysis following the exclusion of the strongest individual yielded different results. This is illustrated by fig. 4, which shows change in standard deviation of position and velocity across the entire weight range, with subjects grouped in bins by MVC results. The rightmost two columns represent the single strongest individual. When excluding the strongest subject, a clear and significant trend is found across bins. This trend is obscured when regarding the data pool on individual basis because of the large variation in the middle bins.

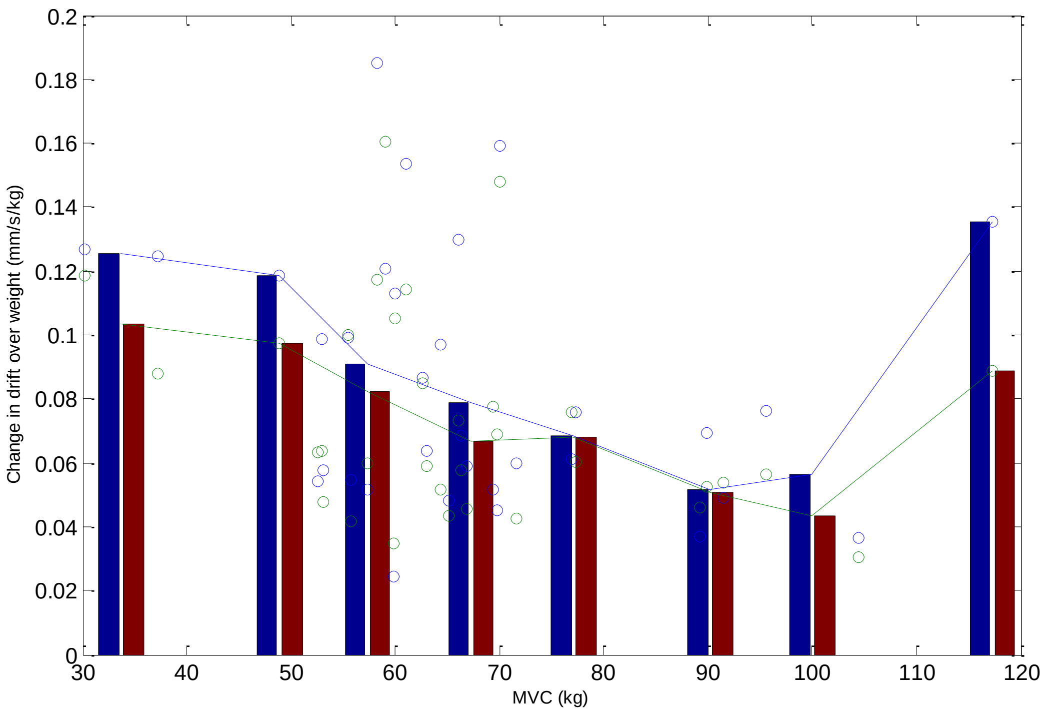


Figure 4: Change in Standard Deviation of Position and Velocity across the Weight Range

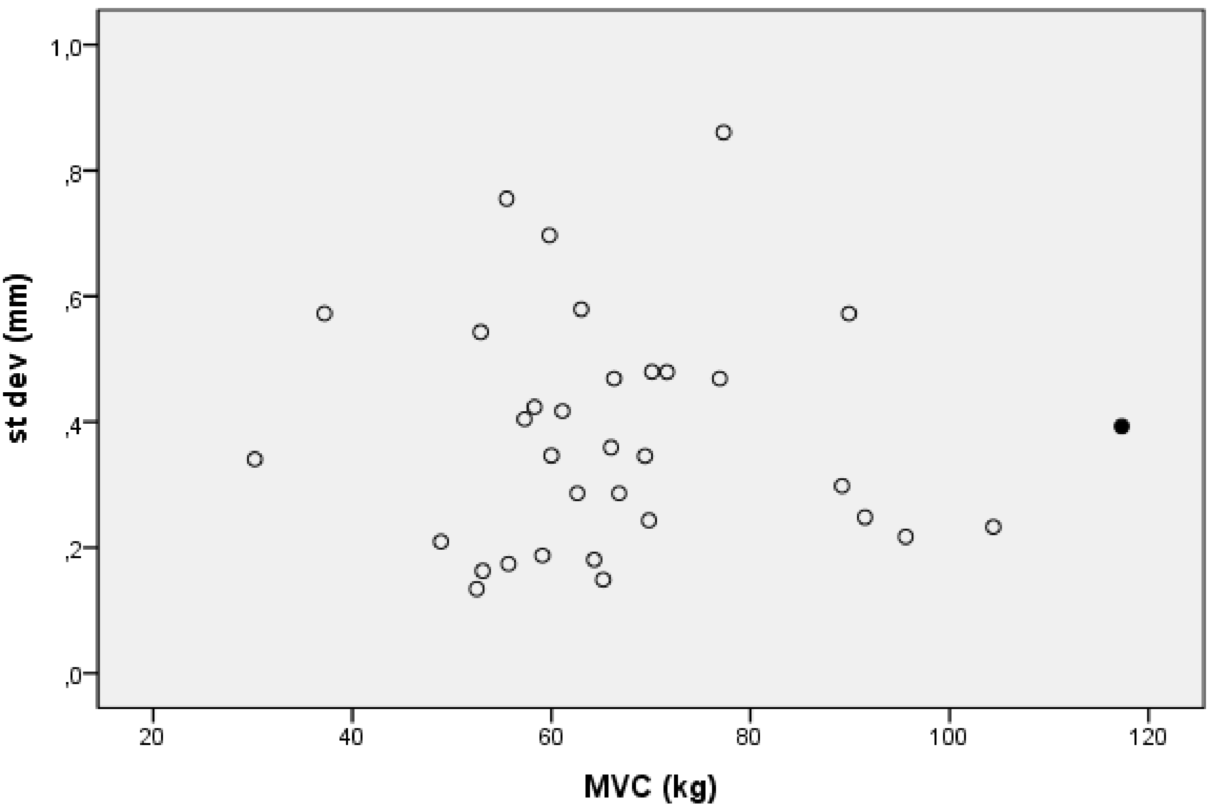


Figure 5: Standard Deviation of Position at 0.5kg

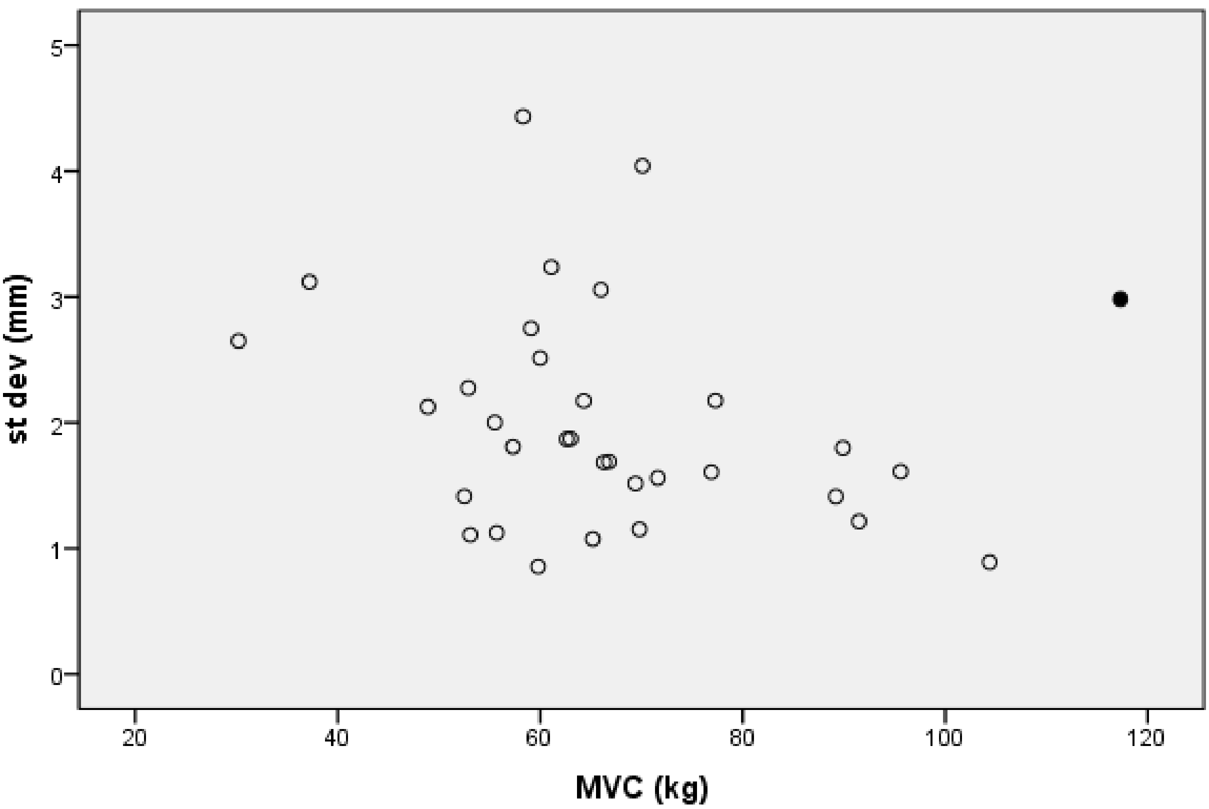


Figure 6: Standard Deviation of Position at 20kg

Figures 5 and 6 show standard deviations of position for all participants at 0.5 and 20kg, as well as the atypical performance of the strength outlier, which is represented by a solid black dot. Removal of the outlier resulted in the correlational values for MVC shown in table 3. There is a significant correlation between MVC score and standard deviation of position at 10, 15, and 20kg after removal of the outlier. Stronger individuals tended to display lower variability at the three greatest loads. At lower levels of force, no significant correlation between strength and variability was found. No significant correlations were found between MVC and standard deviation of velocity and acceleration, drift and mean position either. Still, some tendencies are noticeable. Stronger individuals may have tended to have had lower standard deviations of velocity at the highest force levels

	St dev position	**St dev velocity**	**St dev acceleration**	**Mean Position**	**Drift**
0,5kg	R: -0.048 P: 0.793	R: 0.105 P: 0.567	R: 0.116 P: 0.527	R: 0.239 P: 0.187	R: -0.038 P: 0.836
1,25kg	R: 0.153 P: 0.402	R: 0.147 P: 0.422	R: 0.099 P: 0.592	R: 0.180 P: 0.324	R: 0.229 P: 0.208
2,5kg	R: -0.177 P: 0.332	R: -0.134 P: 0.466	R: -0.078 P: 0.672	R: 0.235 P: 0.196	R: 0.034 P: 0.852
5kg	R: -0.281 P: 0.119	R: -0.246 P: 0.174	R: -0.134 P: 0.466	R: 0.306 P: 0.089	R: 0.054 P: 0.769
10kg	**R: -0.364 P: 0.040**	R: -0.256 P: 0.157	R: -0.041 P: 0.825	R: 0.273 P: 0.131	R: -0.005 P: 0.980
15kg	**R: -0.372 P: 0.036**	R: -0.320 P: 0.074	R: -0.080 P: 0.662	R: 0.324 P: 0.070	R: 0.122 P: 0.506
20kg	**R: -0.350 P: 0.050**	R: -0.338 P: 0.058	R: -0.223 P: 0.219	R: 0.250 P: 0.167	R: -0.022 P: 0.906

Table 3: Correlational Values for MVC without Strength Outlier

%MVC	N	R-value	P-value	%MVC	N	R-value	P-value
<1%	28	-0.105	0.596	**15-19.9%**	26	-0.128	0.532
1-1.9%	20	0.177	0.456	**20-24.9%**	17	-0.119	0.649
2-2.9%	19	0.036	0.885	**25-29.9%**	18	-0.146	0.563
3-4.9%	27	0.190	0.324	**30-39.9%**	19	0.086	0.727
5-9.9%	32	-0.038	0.366	**40-49.9%**	3	-	-
10-14.9%	13	-0.524	0.066	**>50%**	2	-	-

Table 4: Correlational Values for MVC and Standard Deviation of Position at %MVC

	FFT mean position	FFT mean velocity	FFT mean acceleration	FFT max position	FFT max velocity	FFT max acceleration
0,5kg	R: -0.147 P: 0.421	R: 0.012 P: 0.948	R: -0.077 P: 0.675	R: -0.243 P: 0.181	R: 0.254 P: 0.161	R: -0.050 P: 0.788
1,25kg	R: -0.082 P: 0.654	R: -0.153 P: 0.403	R: -0.038 P: 0.837	R: -0.023 P: 0.899	R: -0.142 P: 0.440	R: -0.099 P: 0.588
2,5kg	R: 0.111 P: 0.546	R: -0.146 P: 0.427	R: 0.118 P: 0.518	R: 0.146 P: 0.425	R: -0.096 P: 0.603	R: 0.183 P: 0.316
5kg	R: 0.096 P: 0.601	R: 0.260 P: 0.150	R: 0.236 P: 0.193	R: 0.081 P: 0.661	R: 0.249 P: 0.169	R: 0.225 P: 0.215
10kg	R: 0.045 P: 0.806	R: 0.293 P: 0.104	R: 0.185 P: 0.311	R: 0.155 P: 0.397	R: 0.268 P: 0.137	R: 0.273 P: 0.130
15kg	R: 0.116 P: 0.526	R: 0.145 P: 0.430	R: 0.139 P: 0.449	R: -0.092 P: 0.616	R: 0.040 P: 0.827	R: 0.243 P: 0.181
20kg	R: -0.064 P: 0.728	R: 0.058 P: 0.754	R: 0.069 P: 0.707	R: 0.043 P: 0.815	R: -0.027 P: 0.883	R: -0.239 P: 0.188

Table 5: Correlational Values for MVC without Strength Outlier

MVC results did not correlate with standard deviation of position at any of the percentage intervals presented in table 4. Adjusting the 10-14.9% interval to include values +2.5-5.0% in either direction, leading to the inclusion of additional subjects, did not result in a stronger or significant correlational value. As can be derived from table 5, MVC results did not correlate with mean or max frequency of position, velocity or acceleration at any level of force. This was also the case with median frequency values of the same signals.

No significant correlation existed between MVC and thigh circumference for the group as a whole. However, removal of the two strongest and the two weakest subjects yielded a significant R-value of 0.398 (P: 0.032), indicating a moderate correlation.

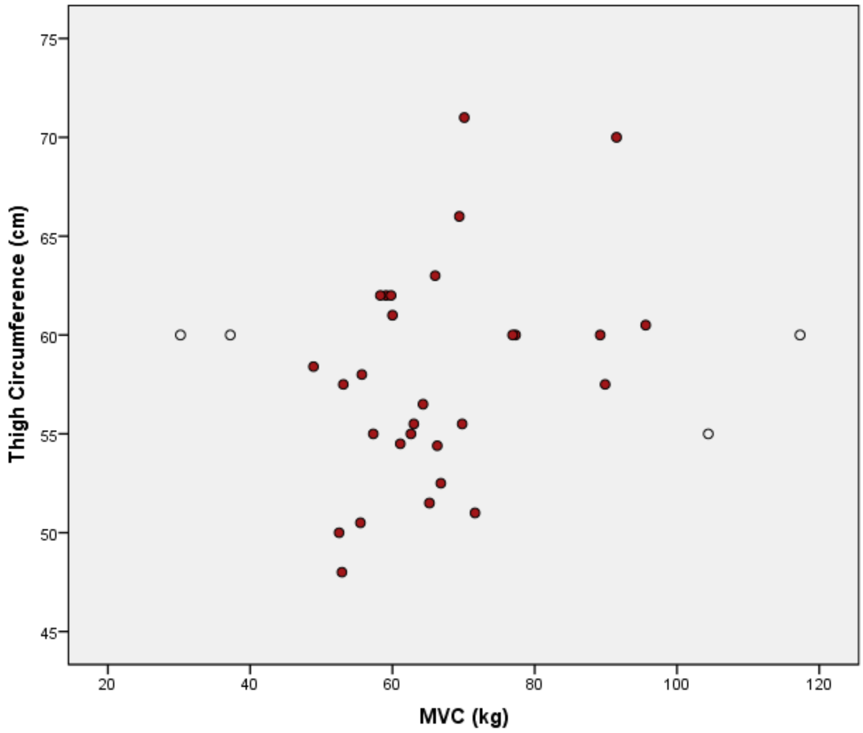


Figure 7: Thigh Circumference and MVC Results

	MVC	MVC w/o outliers
Thigh Circumference	R: 0.205, P: 0.252	R: 0.398, **P: 0.032**

Table 6: Correlational Values for MVC and Thigh Circumference

Thigh circumference did not correlate with standard deviation of acceleration or with standard deviation of position at any force level, and the only significant correlation between standard deviation of velocity and thigh circumference was at 20kg (n=33), with an R-value of 0.439 (P: 0.011). Removal of the aforementioned outliers based on MVC, did not yield significant results.

Lower-leg length showed no significant correlation with MVC, thigh circumference, standard deviation of position, standard deviation of velocity, or mean or maximum frequency of position. However, for standard deviation of acceleration, lower-leg length was somewhat correlated with results at 10 (R: 0.368, P: 0.035) and 15kg (R: 0.366, P: 0.036).

Mean standard deviation of position for the first two trials at 1.25kg amounted to 0.488mm, while the mean for the last two trials at the end of the testing protocol was found to be 0.541. The 0.053mm difference was not statistically significant (P: 0.34). The same held true for performance at the first versus second trial at 1.25kg, and the third versus fourth, with no significant difference between either pair.

Load and variability

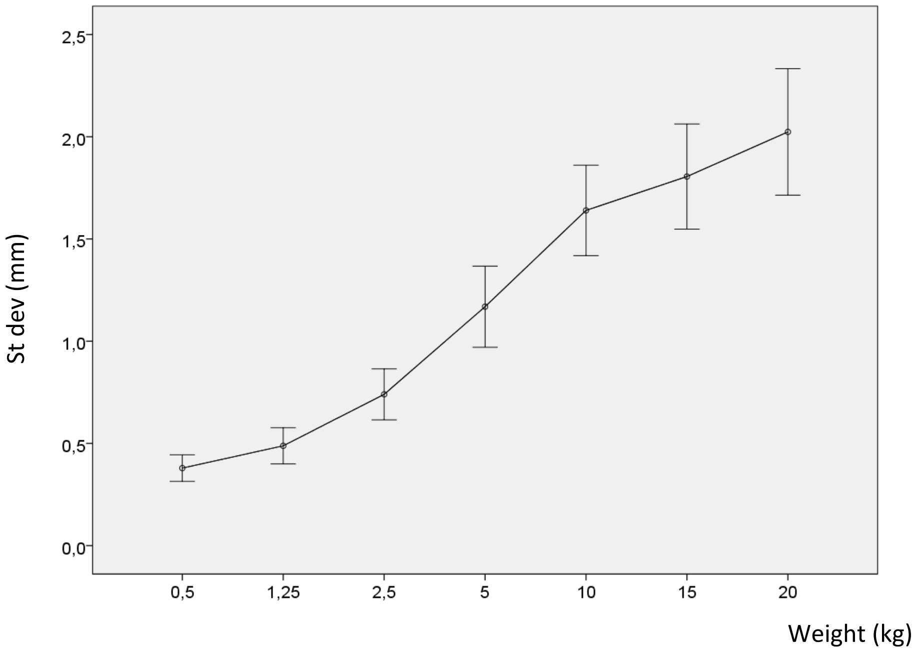


Figure 8: Means for Standard Deviation of Position

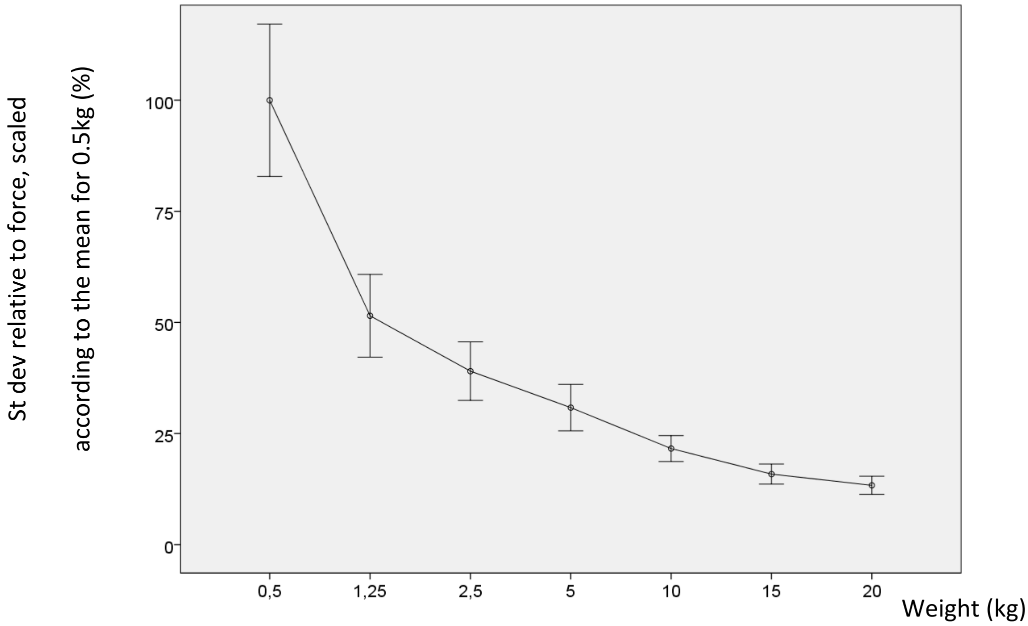


Figure 9: Standard Deviation of Position Relative to Force

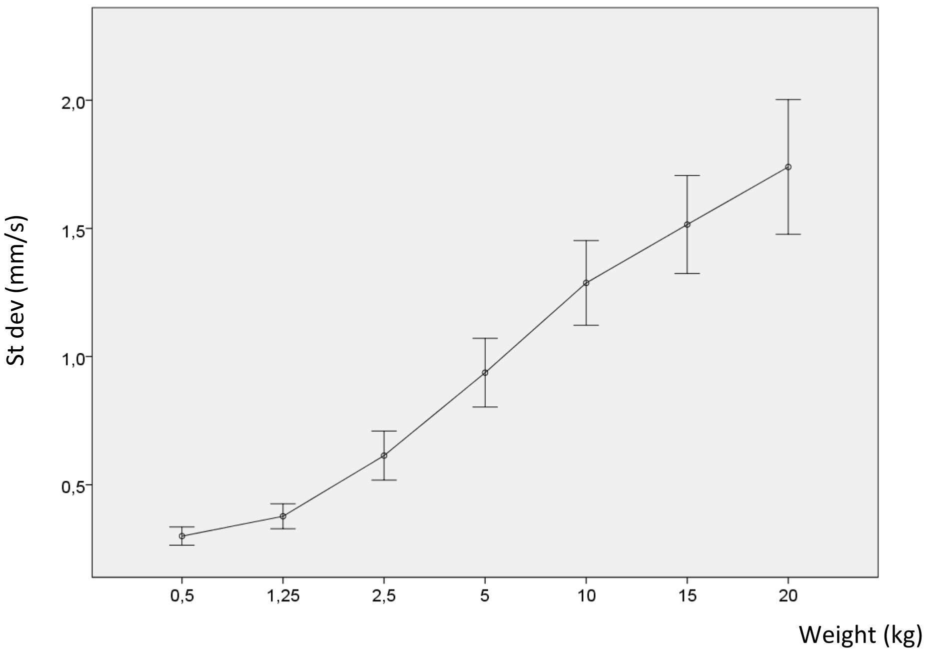


Figure 10: Means for Standard Deviation of Velocity

While figure 8 shows how means for standard deviation of position increased as a function of weight, figure 9 demonstrates how position variability relative to load was at its highest at 0.5kg, and decreased with added weight. Means for standard deviation of velocity (Figure 10) exhibited a relationship with load very similar to standard deviation of position, while means for standard deviation of acceleration increased with weight as well, albeit in a slightly different fashion.

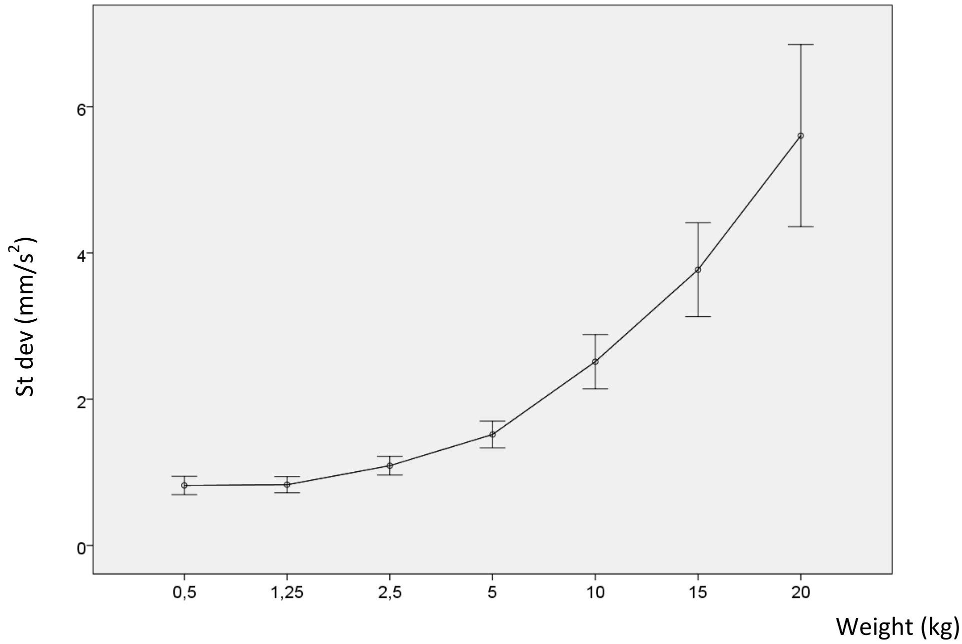


Figure 11: Means for Standard Deviation of Acceleration

Subjects had their standard deviations of position, velocity and acceleration increase by 0.08 mm (P< 0.01), 0.07 mm (P< 0.01) and 0.24 (P< 0.01) per 1 kg increase in load. When mean position across all levels of resistance was plotted for all subjects (n=33), mean position was found to decrease by 0.64 mm on average for each 1 kg increase in weight (P: 0.04). Standard deviation of position increased with 0.08mm (P<0.01), standard deviation of position with 0.07mm (P<0.01) and standard deviation of acceleration with 0.24mm (P<0.01) per 1kg increase in load.

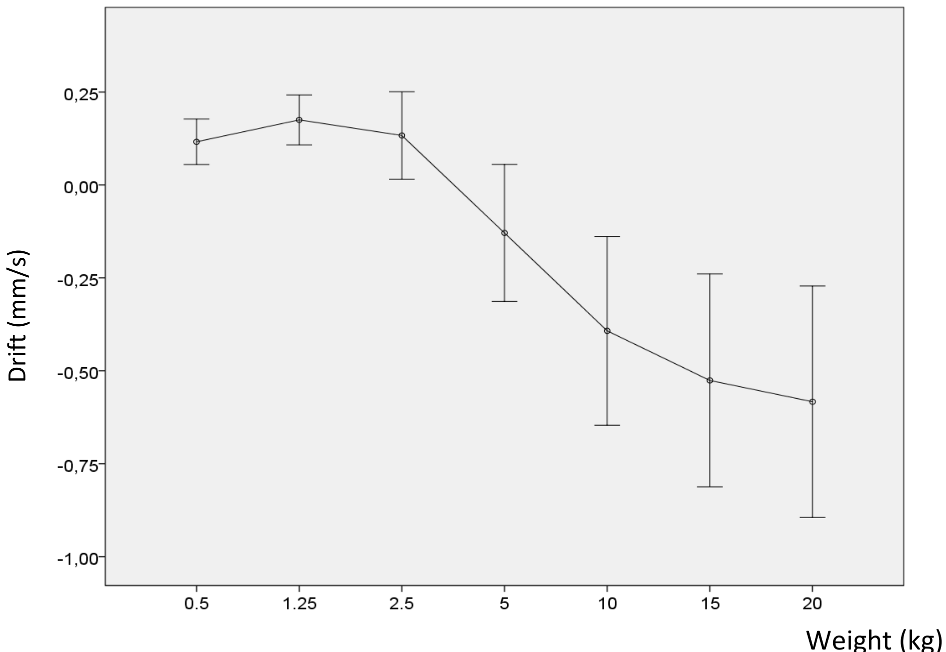


Figure 12: Drift

Figure 12 shows drift at each weight. At 0.5, 1.25 and 2.5kg, subjects drifted at an average of 0.12, 0.18 and 0.13 mm/s in the forward direction (95%CI>0), while the reverse proved true at 10, 15 and 20kg, with mean values of -0.39, -0.53 and -0.58 mm/s (95%CI<0). On average, subjects drifted -0.04 mm (P< 0.01) per 1kg increase in load.

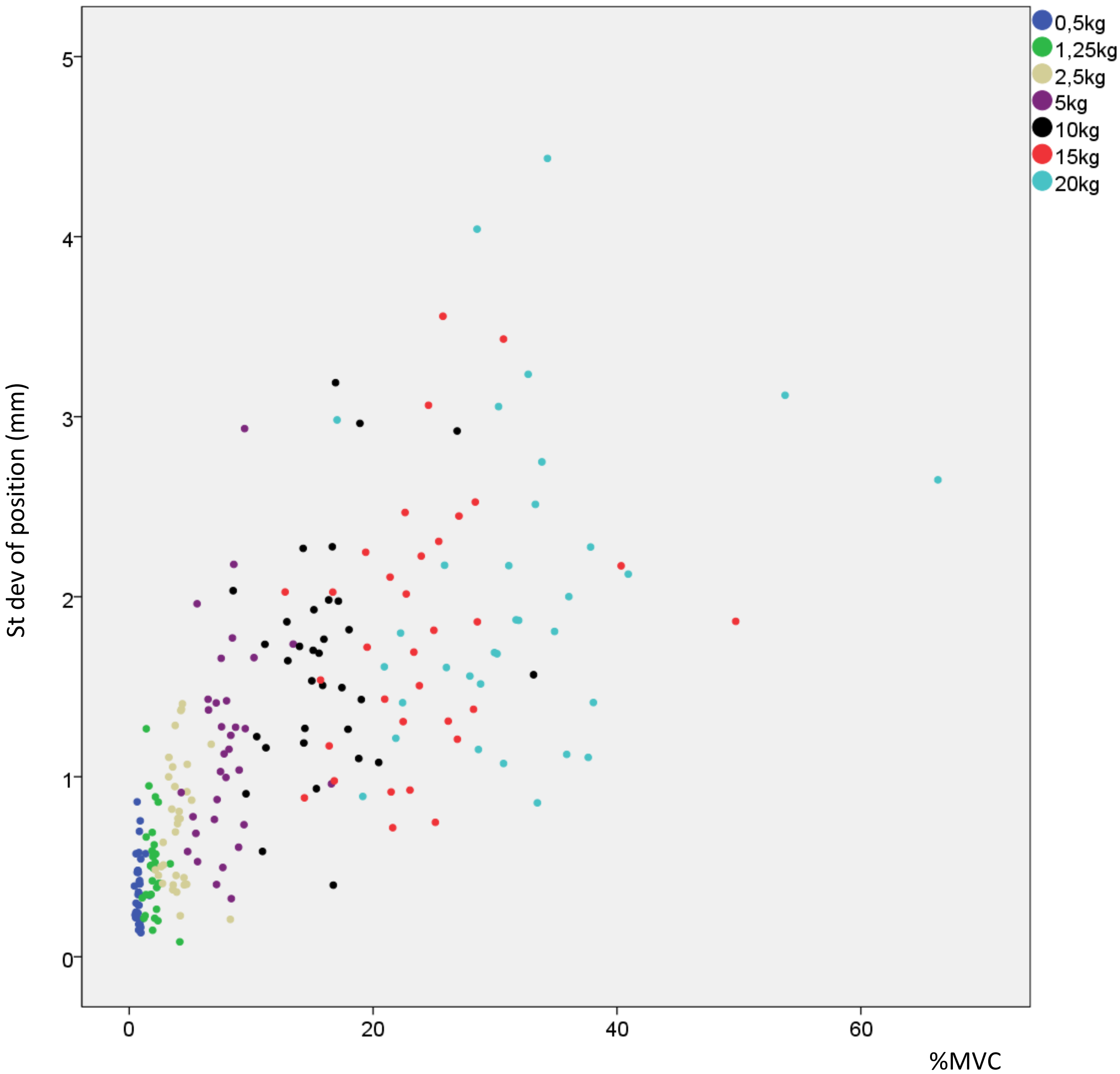


Figure 13: Variability Relative to %MVC

Figure 13 shows how subjects performed according to %MVC, with data points coloured according to absolute load. For the group as a whole (N=32), standard deviation of position was highly correlated with %MVC (R: 0.720, P<0.01). Re-inclusion of the outlier lowered the strength of the correlation somewhat (R:0.693, P<0.01).

Means for the entire subject mass for mean frequency of position (figure 14) varied little between the different force levels, with no significant differences between force levels. It should be noted, however, that inter-subject variation was much higher at the lowest weight (0.5kg), which is reflected in a much wider confidence interval. As for maximum frequency of position (figure 15), subjects, on average, displayed markedly lower maximum frequencies at 1.25kg than between 5 and 20 kilograms of resistance, though not significantly so.

Substantially less intersubject variance is seen with regards to mean frequency of velocity, especially up to and including 10 kg. As can be seen in figure 16, subjects demonstrated increased frequency in the velocity signal at the lower and upper end of the force spectrum. Means for maximum frequency of the velocity signal (Figure 17) display somewhat similar properties, and, as was also the case with mean frequency of velocity, inter-subject variance was at its definite lowest at 5kg. Mean and maximum frequencies of the acceleration signal were also found to have a somewhat U-shaped relationship with weight (Figures 18 and 19).

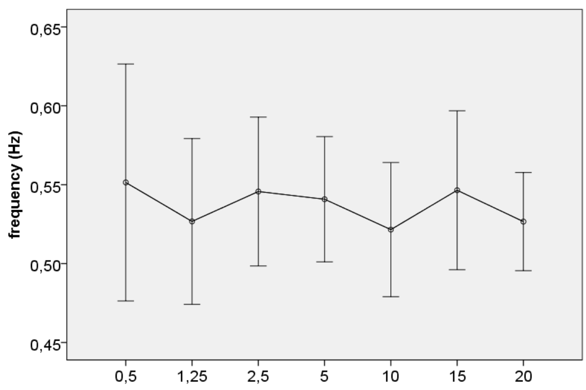


Figure 14: Means for Mean Frequency of Position

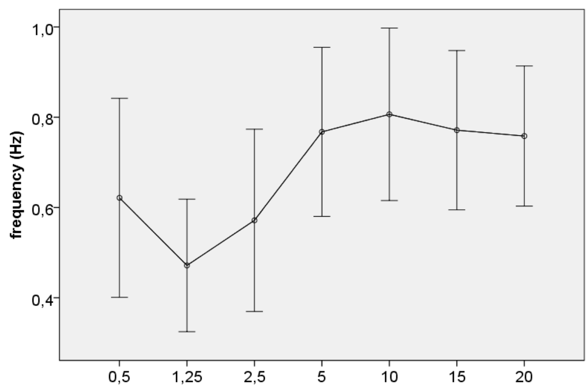


Figure 15: Means for Maximum Frequency of Position

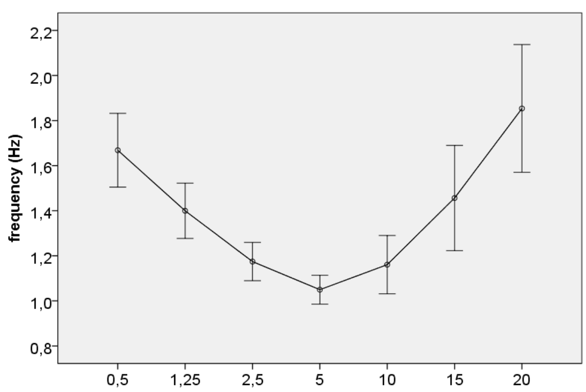


Figure 16: Means for Mean Frequency of Velocity

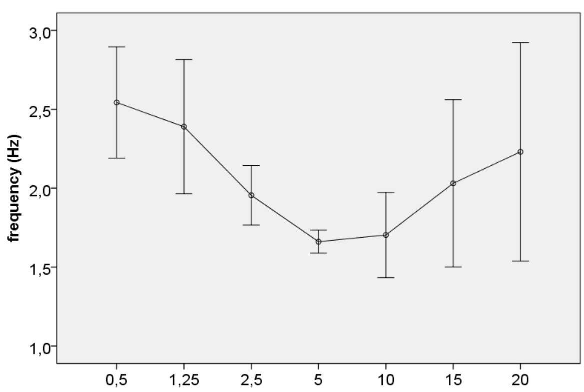
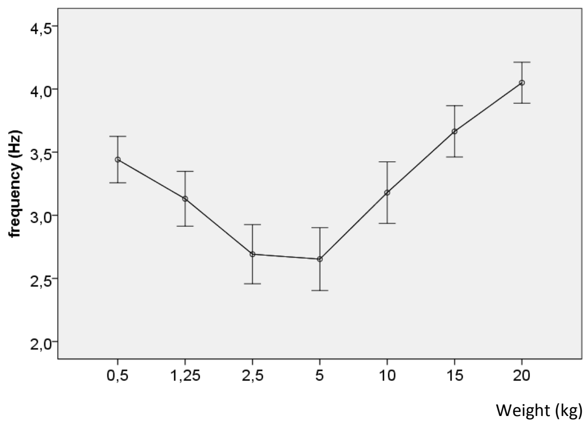


Figure 17: Means for Maximum Frequency of Velocity

Weight (kg)



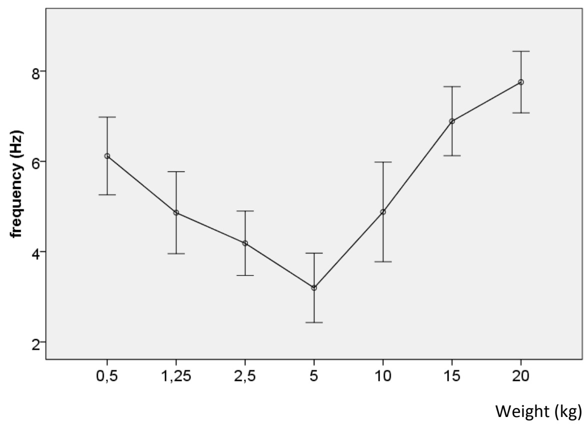


Figure 18: Means for Mean Frequency of Acceleration

Figure 19: Means for Maximum Frequency of Acc.

DISCUSSION

Strength and force variability

Strength did not affect force variability at lower levels of force. At the higher force levels of the testing procedure (10, 15 and 20kg), the stronger individuals exhibited lower levels of force variability. The latter was hardly unexpected. While, for instance, 20kg represented over 65% of MVC for the weakest of the subjects, and around 32% of MVC for those with strength in the area of the mean, for the strongest subjects, the same weight amounted to no more than 17-20% of MVC. Knowing the general trend of variability relative to %MVC (Laidlaw et al., 1999; Slifkin & Newell, 2000; Christou et al., 2002; Taylor et al., 2003), the lower variability displayed by the stronger subjects at the highest force levels hardly seems surprising. Nevertheless, seeing a good correlation between MVC results and force control at as low a force level as 10kg (average: 16%MVC) is an important finding, especially when taking into account the variable results of the numerologically superior mid-strength participants. This implies that strength training may contribute positively to force control even at relatively low force levels. The main mechanism responsible is probably that of increased strength leading to absolute weights representing a lower %MVC, causing less force variability in accordance with the aforementioned relationship between variability and

%MVC force level. While this effect has been demonstrated in elderly subjects (e.g. Keen et al., 1994; Laidlaw et al., 1999; Bilodeau et al., 2000; Beck et al., 2011), studies on young and strength trained populations have typically omitted measurements at absolute force levels, and the subject has been given comparatively little emphasis even after performance at %MVC scaled relative to absolute generated force has hinted towards the effect (Smits-Engelsman et al., 2008).

Significant correlations were not obtained at 0.5-5kg. The 0.75kg increase in weight between 0.5 and 1.25kg resulted in a 0.11 mm (P<0.05) increase in mean standard deviation position, while 2.5kg yielded a 0.25mm increase (P<0.01) over 1.25kg (figure 8). Seeing how relatively small weight increments altered performance, it was somewhat surprising to find that subjects did not differ significantly in performance at the lower force levels according to MVC on the basis of varying relative load (%MVC). While understandable at for instance 0.5 and 1.25kg, where the weights represented the relatively small spans of 0.43-1.66% and 1.07-4.14% of MVC, results at 2.5 and 5kg might at first seem a bit more puzzling. It seems probable that the distribution of strength, among the participants could be a determining factor, the dominating and highly variable mid-strength group obscuring what might be a trend of differing performance between the very strongest and the very weakest. However, the low number of participants situated at either end of the strength scale must be taken into consideration, as it leaves little room for any definite conclusion as to such statistical trends.

The lack of any evidence for the theorized absolute expansion of the lower zone of increased relative variability leaves for a far more complex interpretation. Smits-Engelsman et al. (2008) reported no significant differences based on strength with regards to force control at set percentages of MVC, and the same held true for the present study. Standard deviation of position was highly correlated with %MVC (R: 0.720, P<0.01), and a true lack of strength based difference in variability at relative (%MVC) force levels would logically imply an absolute expansion of the relative variability curve in stronger subjects. Thus, we had theorized that the previously described lower zone of increased relative variability would encompass a larger segment of the absolute strength span of such subjects.

There are several potential explanations for the lack of strength based difference in variability at the lower force levels. One possibility is quite simply that the strongest subjects in this study might not have been sufficiently strong and in possession of large enough type-I fibers to make for a measurable difference. Several factors affect and contribute to strength, and even though the stronger subjects in this study very likely possessed greater quadriceps physiological cross sectional area, the probable difference need not have been very pronounced, at least not in participants not far above mean strength level. This, coupled with greatly varying performance in the mid-strength group, would lead one to believe that the present findings cannot completely rule out the possibility of truly high levels of strength leading to higher force variability at certain levels of resistance. While MVCs in the unilateral isometric leg extension in this study ranged from 30.2 to 117.3 kilograms, none of the participants exhibited what could be characterized as high level competitive strength. At a previous bodyweight of 98kg, the strongest subject reported having managed a barbell squat of 200kg This was done to powerlifting (International Powerlifting Federation) depth, where in the bottom position the "top surface of the legs at the hip joint are lower than the top of the knees" (IPF, 2012, p.9), and without the aid of any supportive gear other than a powerlifting belt. While clearly much stronger than what can be described as an average individual, equipment-free powerlifting records are significantly higher, both at regional and international level. As such, the results of this study cannot necessarily be taken as to cover the entire strength spectrum, and conclusions as to force control in even stronger individuals cannot be made, especially seeing as we did not have definite means of determining the scale of type-I fiber hypertrophy in the stronger subjects. Strength still serves as a good indication, but leaves room for a degree of uncertainty. While probably not very practical, in vivo muscle biopsy of participants in future studies, coupled with stronger subjects, would help paint a clearer picture with regards to type-I muscle fiber size among participants.

Even if the stronger subjects had considerably larger type-I fibers than the others, some form of compensatory control mechanism might be existent. As has previously been stated, elderly and untrained subjects have been shown to demonstrate bettered force control following periods of strength training. Kornatz, Christou & Enoka (2005) found that, apart from strength increases, training led to a reduction in discharge rate variability, and a subsequent decrease of force variability in elderly subjects performing finger abduction tasks. Tracy, Byrnes & Enoka (2003) published similar results following a study involving the quadriceps musculature. Literature on the subject is somewhat sparse, but there are some indications that this effect might also manifest itself in young, healthy subjects following a period of training (Duchateu et al., 2006), though most probably of a lesser magnitude. Smits-Engelsman et al. (2008) proposed that variability-reducing alterations in the central drive mechanism may follow prolonged strength training, and noted that Caroll, Barry, Riek & Carson (2001) found that resistance training of the index finger resulted in the muscles being recruited in a more consistent fashion (Smits Engelsman et al., 2008). These effect alongside gains in strength and hypertrophy could serve to mask the potential variability increasing effects of the latter. Another possible explanation has been provided by Hamilton et al. (2004). Testing a small group of adult subjects, the researchers found similar variability results at low force levels for strong and weak muscles. It was theorized that a "lower firing rate [in a] strong muscle will act to decrease its noise, while the low number of units firing will act to increase it, leading to a very similar noise level across the strong and weak muscles".

One could have speculated that the utilization of different control strategies and feedback-loops could mask a potential difference in force control due to hypertrophy and strength level. Smits-Engelsman et al. (2008, p.60) stated that the use of different strategies to control movements "will result in energies at different frequency bands", and presented data showing a strength trained group displaying "more energy in the lower frequency band" (p. 65) than controls. This was taken to indicate greater use of longer feedback loops, as well as providing indications of the strength trained subjects using "a more somatosensory (5-6 Hz) feedback controlled strategy" (p.65). However, no evidence for any difference in control strategies based on strength was found in the present study.

Subjection to training-related tasks demanding high levels of coordination, e.g. any kind of closed kinetic chain strength exercise, could very easily serve to mask possible differences in general force steadiness due to the great advantage presumably held by a large portion of the stronger individuals in such exercises due to training. We believe that the possible influence of task experience was minimized by the characteristics of the positional tasks.

Standard deviations of velocity and acceleration

MVC results did not correlate with standard deviation of velocity or acceleration at any level. Still, stronger individuals may have tended to have lower standard deviations of velocity at the highest force levels, with R-values of -0.320 (P: 0.074) and -0.338 (P: 0.058) at 15 and 20kgs. A significant correlation would have indicated that stronger subjects had slower movement.

Absolute and relative variability

Standard deviation of position showed a significant increase for each increase in weight, displaying linear growth between 5 and 20kg. Variability relative to force level was at its highest at 0.5kg, and declined with added weight to its lowest level at 20kg, which is in agreement with the studies of Galganski et al. (1993), Laidlaw, et al. (1999), Christou et al. (2002), Taylor et al. (2003), and numerous others. This being a weighted positional task, the variability suppressing effect of inertia probably also contributed to this pattern, increasing with load. On average, 20kg represented 32% of MVC for the subjects, and the author believes that the lack of heavier weights did not allow for the increase in relative variability seen in the upper end of the relative force spectrum to manifest itself.

Variability at %MVC

The relationship between variability and %MVC has previously been described as linear (Hamilton, Jones & Wolpert, 2002), exponential (Slifkin & Newell, 1999), and sigmoidal (Christou et al., 2002). Quick analysis reveals that cubic regression provides the best prediction for the whole data range in this study. The cubic regression line shows a sharp increase in standard deviation between the lower percentages, followed by a gradual loss of steepness, approaching horizontal at around 35%MVC. As such, our findings in the area of 0.4-40%MVC do not immediately resemble the models of any of the aforementioned studies. This might in part be due to the low force levels at which measurements were performed. The highly variable performance seen (see fig. 13) is also a very probable culprit, and curve estimation between 5 and 40%VMC produce weak predictive values (r^2: 0.203-0.247) for all curve estimation equations available in SPSS.20.

Different loads, different determinants of variability?

From the above sections, it seems that the level of force control at the opposite ends of the weight span may have been determined by different mechanisms. At the higher end, strength became the main determinant of performance, in the capacity of affecting the relative challenge posed by the absolute loads, as performance in this area correlates strongly with %MVC. Thus, stronger subjects exhibited less position variability here. However, this was not shown to apply at the lower end of the force range. As was touched upon in the opening parts of the discussion, this might at first seem incongruent with the presented findings and literature regarding the correlation between %MVC and standard deviation of position. However, the great majority of the studies postulating the close relationship between variability and %MVC have typically not examined comparatively low force levels. A quick analysis of the 93 values for standard deviation of position <5%MVC in this study yields a significant ($P<0.01$), but weakened correlational value (R:0.471) compared to the one for the entire weight range (R: 0.720). Reducing the measuring window to encompass the 69 data points <3%MVC results in an insignificant R-value of 0.278. Thus, it becomes apparent that the importance of %MVC with regard to performance at very low force levels is greatly diminished, and perhaps even negligible. The aforementioned increase in relative variability and reduction in resolution of force due to a low number of active motor units and a reliance on recruitment to grade force around these levels could perhaps affect variability in such a way as to lead to similar degrees of force fluctuations across a certain force span. However, the precise reason cannot be readily determined within the current study, but should pose an interesting and important subject for future investigation. Some additional insight and more conclusive data could be gained through the use of more measurements at low absolute and relative force levels, using even smaller increments, and with a large number of subjects distributed more equally with regards to strength. Measurements at 0kg could also be included.

Drift and mean position

Interestingly, no significant correlations were found between MVC and drift or mean position. One might have expected strength to affect drift at the higher force levels, where the group as a whole drifted 0.53 and 0.58mm/s backwards (figure12). However, the highly varying values from the mid-strength group greatly affected correlations, and greater number of subjects at either end of the scale might have contributed to a different result. On average, subjects drifted forward at the three lightest weights and backwards at the three heaviest. This shows how weight and, subsequently, the required force production clearly affected the ability to maintain position, and to a certain extent also how subjects tended to produce more or less than the force required to simply counter the posterior pull, which was in turn probably influenced by the inherent precision of the differing feedback- and control strategies utilised.

Frequency content

The frequency content of the positional signal shows variation of force output in the time domain. While influenced by involuntary fluctuations in motor unit firing and recruitment, frequency measures can also serve as an indication of the rate of correctional adjustments, and subsequently also the control strategies employed. The frequency content of isometric force production tasks at various loads has been a subject of investigation, and at least one previous study has reported differences in frequency content between strength trained subjects and controls. Smits-Engelsman et al. (2008) found that their strength trained group exhibited more energy in the lower frequency band, and this was taken as an indication that the strength trained employed longer, somatosensory feedback loops to a greater extent than the controls. As the current data was gathered from a weighted positional task, conclusions as to the employment of specific control strategies cannot readily be made, even though changes in the approach to the task according to the level of resistance seem apparent. As has been shown, MVC results did not correlate with mean, median, or max frequency of position, velocity or acceleration at any level of force, indicating no difference in control strategies based on strength.

Means for mean frequency of position varied little between force levels, though inter-subject variation was higher at 0.5kg. This heightened variation between subjects might have been at least in part due to the trials at 0.5kg making up the very first tests, and some of the variation can therefore be explained by unfamiliarity with the task. The low inertia inherent of such a light weight is a probable contributor as well, necessitating more frequent corrections for some of the subjects. Despite no significant increase in mean frequency, maximum frequency of position increased across the weight span. Average values for mean frequency of position were centered around 0.54Hz.

While derived from position in time, we believe that the frequency contents of the time derivates, i.e., velocity and acceleration signals provide a more sensitive and direct measure of force fluctuations than position. The frequency of position to a greater extent describes the movement outcome, and is, as such, less sensitive to variations in force output that do not necessarily result in changes in the direction of movement. In addition, we found the frequency characteristics of velocity and acceleration to agree with studies on variability in isometric force production.

As well as generally less variation among subjects, mean and maximum frequency of velocity and acceleration showed a clearer trend across trials than position. Mean frequency of velocity was at its lowest at 5kg, and increased at the lower and upper end of the force spectrum; seemingly linearly from 5kg and upwards, with a much greater increase relative to weight in the opposite direction. A similar relationship was observed between load and mean frequency of acceleration, as well as maximum frequency of both acceleration and velocity. Previous studies have reported an inverted U-shape in the complexity of force output between 5 to 95 %MVC (Slifkin & Newell, 1999; Deutsch & Newell, 2001). We found that both mean and maximum frequency of velocity and acceleration was at their highest at either end of the weight range, which represented on average 0.8 and 32.0%MVC for the participants. While care must be taken due to the great variation in strength, the rise in frequency seen from 5kg (average of 8%MVC) and upwards corresponds to the initial increase and first portion of the inverted U-shape described by Slifkin & Newell (1999), as well as agreeing with data of Deutsch & Newell (2001). The increase in mean and maximum frequency at even lower force levels has not been as thoroughly reported, and while Sosnoff et al. (2006) published similar findings for an isometric finger abduction task, this frequency increase at very low force levels has to this author's knowledge not been described for the quadriceps musculature before. Figure 20 shows a strictly conceptual and illustrative model of the relationship between mean frequency of force/velocity/acceleration, placing the current findings in a wider context.

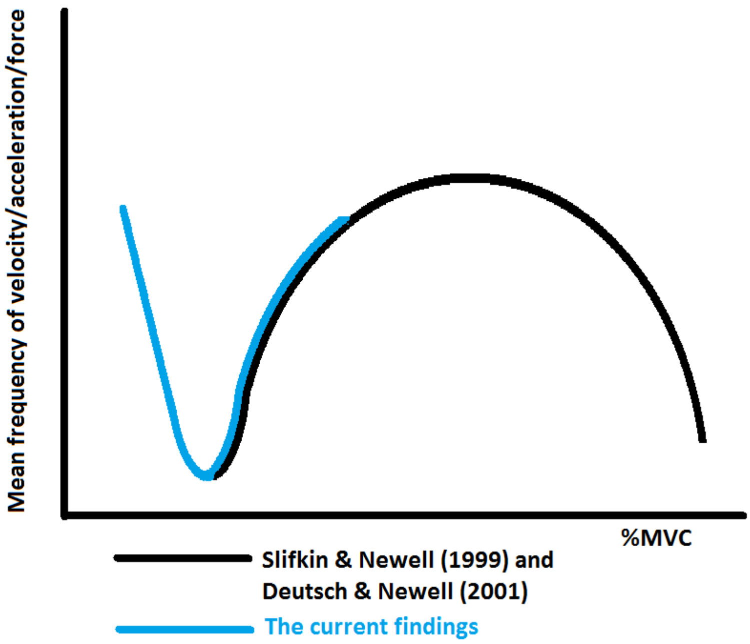


Figure 20: Frequency Findings

Subjects varied surprisingly little in the mean and maximum frequency of velocity at 5kg, despite large variations in MVC and therefore also %MVC for the 5kg. This was also the point around which both maximum and mean frequency of velocity were the lowest. The frequency of the acceleration signal exhibited properties similar to the velocity signal, and mean frequency of acceleration was found to be significantly lower at 2.5 and 5 kg than at 0.5, 15 and 20kg, while maximum frequencies of acceleration tended to be lowest around 5kg. Slifkin & Newell (1999) pointed toward the existence of a region of force production where information transfer related to targeted force production is optimized, which was thought to be the point where the noisiness of the force signal was maximized. We found the best relative control in our study to be at 20kg (average of 31%MVC, see figures 9 and 13), and upwards of 5kg the mean and maximum frequency of velocity and acceleration increased to a maximum at 20kg. However, mean and maximum frequencies also exhibited a similar increase in the other direction, with a second peak at 0.5kg. Relative control was at its worst at the lowest weights, and we can therefore infer that information transfer is not necessarily the main determinant of frequency content under all conditions, or, perhaps more correctly, that increased amplitude at higher frequencies does not automatically translate into better relative performance.

The increase in frequencies at the three lowest weights probably stem in part from the mechanical factor of low inertia. In addition, signal-to-noise ratio has been shown to be low at these force levels (fig.9), which could reasonably manifest itself as more frequent corrections due to the inherent increase in movement corrections from the low relative force control in the positional task. Additionally, Sosnoff et al. (2006) examined force variability in finger abductions at 0.4-4.0N, and stated that the low level of relative control seen at low force levels in conjunction with increases in high frequency content were "due to the inability to perceive and subsequently correct for the small force oscillations" (p.166).

Proof of solid measurements

Several results underscore the validity of the measurements. There was no significant difference in subject performance between the first and last two trials at 1.25kg, demonstrating the probable absence of performance-decreasing fatigue, as well as reliability of measurement. In addition, results from the first MVC-test were highly correlated with subsequent performance in the second (R. 0.854, $P<0.01$). Another element worth considering is the clear increase in variability provoked by weight increases amounting to no more than 0.75kg at the least, showing the precision and reliability of the methods and instruments of measure.

The strength outlier

A single outlier was removed from correlational analysis of the relationship between MVC results and force variability. This was on the basis of strength (2.77 standard deviation above the mean), as well as pronounced atypical performance compared to the other subjects managing over 80kg in the MVC tests, especially at 10, 15 and 20kg. Removal of this outlier resulted in significant correlations between MVC results and standard deviation of position, and strengthened the correlation between standard deviation of position and %MVC.

Thigh circumference

It was deemed probable that stronger subjects would on average also exhibit greater quadriceps PCSA, and thigh measurements were done in the hope of it being able to serve as an indicator of thigh muscularity. The relationship between thigh circumference and MVC results proved statistically significant only after removal of the two strongest and two weakest subjects. One probable reason for this was that the two strongest participants were by visual inspection thought to be among the very leanest, and therefore able to carry a significant amount of thigh musculature at a relatively average circumference. With an r-value of 0.398 (P: 0.032), the correlation for the rest of the group was moderate at best, but existent. Apart from a moderate correlation at 20kg for standard deviation of velocity, thigh circumference was not found to affect performance in any way, not even for standard deviation of position at the heaviest weights. Adding body fat measurements to the equation would probably have made for a better estimate of muscle mass in the present group, but this was omitted primarily due to the level of experience required for skinfold tests to be somewhat accurate. It is this author's belief that thigh circumference in itself is likely to have proven useful if a number of stronger individuals had participated, for instance powerlifters in the higher weight classes, diminishing the influence of fat percentage.

Shin length

The only significant correlations (weak-moderate) for tibial length were at 10 and 15kg for standard deviation of acceleration. We chose not to adjust for shin length during analysis, as we did not find any indications of it affecting performance in the positional tasks. Additionally, the reference position included the shin hanging vertically, and, thus, shin inertia did not affect outcome.

Coactivation

We opted not to measure the magnitude of hamstring coactivation, as the possible influence of antagonist coactivation was outside the scope of this article. In addition certain studies have found coactivation not to correlate with force variability (Burnett et al. 2000, Krishnan et al., 2011).

Concluding remarks

Strength did not affect force variability at lower levels of force. When compounded with results from previous studies, it seems relatively safe to assume that general strength training (if such a thing exists) up to a certain level is non-detrimental to force control at lower levels of resistance. However, results cannot necessarily be extrapolated to even stronger populations, and future research should aim to recruit even stronger participants. At the higher force levels of the testing procedure (10, 15 and 20kg), the stronger individuals exhibited lower levels of position variability, demonstrating that increases in strength can lead to better force control at relatively moderate loads. MVC results were not correlated with the frequency contents of the position, velocity or acceleration signals.

In accordance with previous studies, the standard deviation of position, velocity and acceleration increased as a function of load, while standard deviation of position relative to force decreased with added weight. Across the entire weight range, standard deviation of position was highly correlated with %MVC, and performance at %MVC was not affected by strength. However, at the lowest weights, %MVC did not account for performance, and further study into the precise mechanism responsible should be carried out. A U-shaped relationship between load and mean and maximum frequency of velocity and acceleration for the weight range was also found. This frequency increase at the lower force levels has not previously been reported for the quadriceps musculature.

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