Final Report

Kinetic and Kinematic Comparison Between Versa-Pulley and Free-Weight Front Squats

Submitted by:

Andrew C. Fry, Ph.D., CSCS
Director, Exercise Biochemistry Laboratory

Brian K. Schilling, Ph.D., CSCS
Director, Neuromechanics Laboratory

Corey A. Lohnes, BScKin., CSCS
Project Coordinator

Department of Health & Sport Sciences
The University of Memphis
Memphis, TN 38152
901-678-3479 (office)
901-678-3464 (fax)
afry@memphis.edu

February 12, 2007

Table of Contents

Introduction

Resistance exercise has been shown to increase muscular force and mass (Sale & McDougall, 1981; Tesch, 1988), as well as maintain and even increase bone mineral density in load-bearing long bones (Colletti et al, 1989; Dalen & Olsson, 1974). Resistance exercise is accomplished by performing work against an external load, typically caused by the acceleration of gravity applied to a mass. While this is the easiest and most practical means of providing resistance, loading can also be accomplished by use of alternative methods such as rotational inertial resistance.

Traditional free-weights use loading caused by the acceleration of gravity to provide resistance. Because the mass of the load does not change, the resistance experienced by the muscles can vary greatly throughout the range of motion depending on the joint angle, the length of the muscle and the length of the moment arm. The result is that the magnitude of the load one is capable of lifting through a range of motion is limited by their strength at the weakest point in that range of motion. Moreover, since maximal force capabilities of eccentric muscle actions are greater than concentric actions (Tesch et al, 1990a; 1990b), the amount of eccentric loading is typically limited by the amount that can be lifted concentrically.

Another drawback of many traditional free-weight exercises is that movement velocity must be reduced near the extremes of the range of motion in order to perform the exercise in a safe and practical manner. The squat jump and the bench press throw are examples of exercises where maximal movement velocity is encouraged throughout the concentric portion of the range of motion. However, special equipment and trained personnel are usually required to ensure safety during such lifts. Therefore, most free weight training utilizes the traditional approach of decelerating the load near the end of the range of motion to ensure safety. This technique may, however, be less effective in producing optimal training outcomes due to this deceleration at the end of the range of motion. Ideally, resistance training devices would allow the user to exert maximal effort and acceleration through as much of the range of motion as possible. Rotational inertial resistance devices may allow the user to accelerate through a greater range of motion than traditional free weight exercises because the user does not have to be concerned with controlling a load.

Rotational Inertial Resistance (RIR)

RIR devices use the principle of rotational inertia to induce loading during resistance training. Typically, a tether is attached to and wound around a disc at a given distance from the axis of rotation. By pulling the tether, a torque is applied to the disc, setting it into rotation. Because the disc has mass, it also has rotational inertia, which is the property of an object to resist changes in angular motion. The rotational inertia of the disc is positively correlated with the difficulty of accelerating the system. While the system may be set into motion using minimal force, applying a maximal force throughout the range of motion will result in maximal acceleration and velocity. Since the rotational inertia of the disc counters the efforts of the individual, greater muscular effort will result in greater resistance experienced by the individual.

As the tether unwinds from the disc during the concentric portion of the exercise, kinetic energy is built up. Once the individual reaches the end of the concentric range of motion, the tether is completely unwound. At this point, the disc will continue to spin due to kinetic energy, rewinding the tether around the disc. This becomes the eccentric portion of the exercise, and it during this period that the individual resists the pull of the tether to slow the disc.

Because the kinetic energy from the concentric portion of the exercise is transferred to the eccentric portion, an equal eccentric impulse is necessary to halt the rotation of the disc. Since impulse is a function of both force and time, we can induce a greater amount of eccentric average force by performing the eccentric portion in less time than the concentric portion. This, however, can only be accomplished with a shorter eccentric range of motion which is less than ideal. Either way, RIR devices may provide adequate stimulation during both concentric and eccentric actions even though eccentric strength is greater than concentric strength. An additional benefit of RIR devices is that gravity does not affect the kinetics so the magnitude of loading can be more adaptive throughout the range of motion. This form of resistance can be considered "accommodating" since the resistance experienced by the user is directly related to their effort as opposed to their strength at any given point in the range of motion.

A new RIR device called the Versa-Pulley™ has been developed. The Versa-Pulley™ features a tether wrapped around a vertical cone-shaped shaft. The tether is secured at the top of the cone where the small radius is located. At the bottom of the shaft, two perpendicular horizontal bars measuring 60 centimeters in length intersect the axis or rotation. At the end of the bars, weights of different masses can be loaded to modify the moment of inertia of the cone. The tether winds around the cone in a similar fashion to the YoYo™ (Berg, Tesch; 1994), where the concentric action unwinds the tether and the eccentric action occurs during rewinding. Positioned lateral to the cone is an adjustable pulley, which positions the tether at different angles to the cone. With the pulley set at the bottom position, the tether will wrap predominantly around the larger radius of the cone, allowing the user to apply more torque to counter the inertia of the cone. At the top pulley position, the tether will wrap around the smaller radius, so that less torque will be produced at a given force output.

The combination of the cone, adjustable pulley, and interchangeable counter weights allows for a wide range of configurations. Because torque is directly proportional to the length of the moment arm (distance between the axis of rotation and the line of action of the force), and the amount of applied force, the position of the tether on the cone dramatically affects the difficulty associated with rotating the cone. Since the tether is attached at the top of the cone and descends as it winds, the greatest amount of torque will be produced at the beginning of the range of motion and will decrease as the tether unwinds, provided the force on the tether remains the same. Theoretically, if the individual maintains a constant level of force through the movement, torque will gradually decrease as the tether unwinds, resulting in a gradually decreasing acceleration. On the other hand, if one is to maintain constant acceleration, a progressive increase in force output will be required. The opposite occurs during the eccentric portion, where the individual will be required to decrease their force output as the tether winds in order to maintain a constant negative acceleration. Additionally, as mentioned earlier, performing the eccentric action with a shorter range of motion will increase average eccentric force.

The other two adjustable features add additional variability. The moment of inertia can be greatly manipulated by added or removing counterweights, theoretically resulting in very slow or vary fast movement velocities. Modifying the adjustable pulley dictates the moment arm of the tether and thus the velocity level.

While limited research has been conducted on the Versa-Pulley™ and similar devices in the past, there exists no data in regards to the kinetic and kinematic properties of the Versa-Pulley™. Therefore, the objectives of the present study were as follows;

Primary Objective –

To compare the kinetics (force, power, impulse) and kinematics (velocity, acceleration) of front squats performed using the Versa-Pulley™ and traditional free weights.

Secondary Objectives –

1) To compare the kinetics and kinematics of Versa-Pulley™ front squats using the traditional cone shaft and a custom straight shaft.

2) To compare the kinetics and kinematics of various Versa-pulley™ settings during front squats.

Hypotheses

1) The front squat kinetics and kinematics would be similar when performed using the free weights and the Versa-Pulley™.
2) The larger counterweights would produce greater forces but slower velocities and accelerations.

3) The high-velocity pulley setting would result in higher velocities and lower forces when compared to the slow-velocity pulley setting.
4) The straight shaft would produce higher forces and lower velocities across all counterweight conditions when compared with the cone shaft.

METHODS AND PROCEDURES

Subjects

Eleven apparently healthy men (18-35 yrs) were recruited to participate in this investigation. Due to the nature of the protocol, only trained subjects were allowed to participate. Trained status was operationally defined as having the ability to perform a one repetition maximum (1 RM) in the front squat with a load ≥ 100% of bodyweight, in addition to self-reported performance of lower-body resistance exercise ≥ 1 session per week for the past 3 months. All subjects completed health history and physical activity questionnaires in order to determine eligibility. Descriptive data are summarized in table 1.

Testing

During the subjects' initial visit to the lab, health history, drug and dietary supplement usage, and physical activity questionnaires were completed in addition to height and weight measurements. Prior to participation, each subject was informed of all procedures, potential risks, and benefits associated with the study through both verbal and written form in accordance with the procedures approved by the University Institutional Review Board for Human Subjects Research. Potential recruits signed an informed consent form prior to being admitted as a subject.

On the same day, subjects performed a 1 RM countermovement parallel front squat with a barbell. The front squat was performed using a special front squat harness that sits on the shoulders and allows the bar to rest on pegs located at shoulder level (Figure 1 – Appendix C).

The maximum amount of weight lifted one time was recorded as the 1 RM and was used to calculate loads during subsequent free weight testing sessions. Following determination of 1 RM, subjects were instructed both verbally and visually on performance of the parallel squat exercise on the Versa-Pulley™. The Versa-Pulley™ was configured with the tether threaded through a pulley attached to the platform. The end of the tether was attached to the same shoulder harness used during the free-weight front squats (Photo 4 – Appendix C) so the participants could pull vertically on the tether. Participants then performed three sets of three repetitions at both slow and fast velocities in order to familiarize themselves with the movement and device.

At least 48 hours after determination of their 1 RM, subjects reported to the laboratory for their first of six testing sessions. Each session consisted of dynamic performance tests using either free weights (FW) or the Versa-Pulley™ system. All sessions were conducted on separate days with at least 48 hours separating visits to minimize any effects of fatigue. There were two Versa-Pulley™ protocols and one free-weight protocol. One of the Versa-Pulley™ protocols incorporated the use of a constant-diameter shaft (SS) while the other used a cone-shaped shaft (VC). Each of the three protocols was repeated to obtain reliability data, thus assuring valid data were obtained.

Upon arriving for each session, subjects performed a generalized warm-up consisting of a 3 minute cycle on a cycle ergometer, 2 sets of 10 body weight squats, and 2 sets of front squats with 30% 1 RM. Subjects then began one of the three protocols. For the FW sessions, two sets of three repetitions of the countermovement parallel front squat were performed using loads of 45, 65, and 85% 1 RM for a total of six sets. Upon command, subjects were instructed to lower themselves in a controlled fashion to a point where the back of the thigh was parallel to the floor, then immediately return to the starting position using full and controlled effort. Testing was performed while standing on a single-component customized force platform capable of measuring vertical ground reaction force. A linear velocity transducer was also attached to the middle of the barbell in order to measure vertical bar displacement, velocity and acceleration. Subjects were positioned so the velocity transducer line was perpendicular to the floor. Pictures of Versa-Pulley and free- weight equipment configurations can be found in appendix C. The order of the loads was counterbalanced to minimize any order effect. Subjects were given approximately two minutes of rest between each set. This session was then replicated within five days.

The Versa-Pulley™ testing was split into two sessions; VC and VS. For each session, subjects performed 2 sets of 3 repetitions using each Versa-Pulley™ setting with 2 minutes separating each set. The Versa-pulley™ tether was attached to the shoulder harness below the sternum, and subjects were positioned so the tether hung approximately vertical. A strain gauge was placed in line with the tether to measure force exerted by the subject, and a linear velocity transducer was also attached to the harness to measure velocity. Subjects began in the bottom position and were instructed to perform two sub-maximal repetitions to initiate rotation of the shaft then followed immediately with 3 maximal repetitions with no pause between repetitions. The order of conditions within each session was counterbalanced. However, due to the time and effort involved in switching between the cone shaft and the straight shaft, the order of the sessions was not randomized. The various conditions during each session are listed:

Conditions

Cone shaft (12 sets)

2 kg counterweight (2kg), high velocity pulley setting (HighVel)

2kg, low velocity pulley setting (LowVel)

4kg, HighVel

4kg, LowVel

8kg, HighVel

8kg, LowVel

Straight Shaft (SS) (6 sets)

2kg Counterweights

4kg Counterweights

8kg Counterweights

The force platform and strain gauge were both interfaced with an analog-to-digital conversion board. Data was sampled at 1000Hz and analyzed using DataPac® 2K2 v.3.11 software. A low-pass, 4th order Butterworth filter with a cut-off frequency of 30Hz was used for data smoothing. Displacement was obtained by taking the first integral of the velocity channel while acceleration was obtained by taking the first dirivative of the velocity channel with respect to time. Power was obtained by multiplying the velocity and force channels. Impulse was obtained by taking the integral of the force channel with respect to time. Concentric and eccentric impulse was then combined for each repetition to give total repetition impulse.

Each working repetition from every set was separated into an eccentric and concentric component. The onset of the concentric portion was set at the lowest point on the displacement curve prior to the concentric movement, and the offset was set at the top of the range of motion (Figure 1). The eccentric portion was designated in a similar fashion where the onset was set at the top of the range of motion and the offset was set at the bottom of the range of motion (Figure 2).

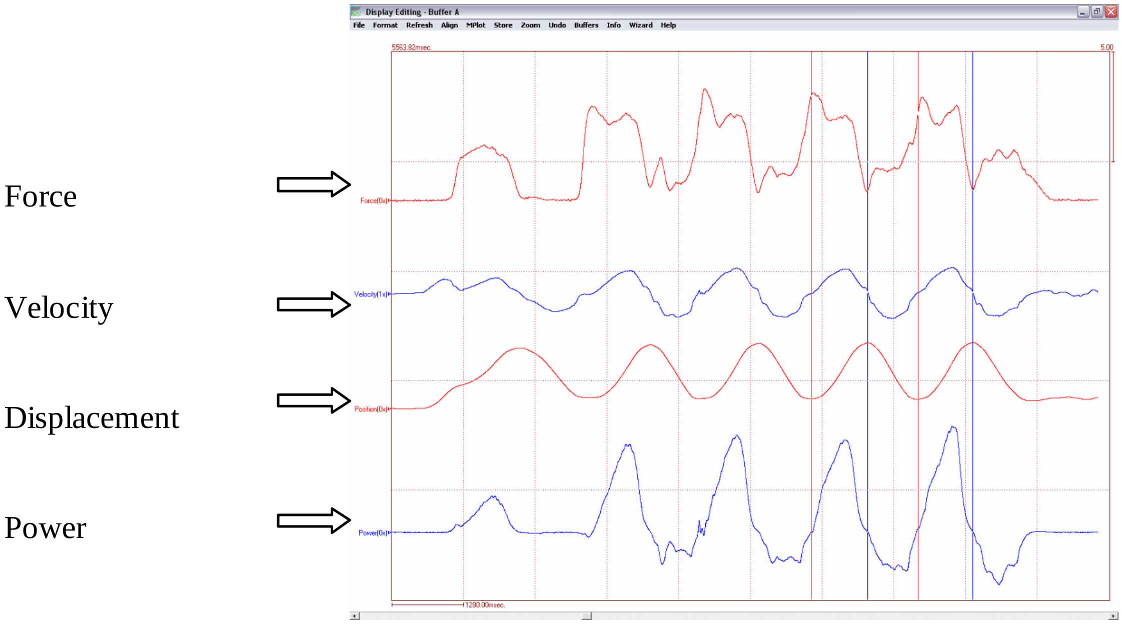


Figure 1 – The onset of the concentric portion of the squat (vertical red lines) occurs at the lowest point on the displacement curve for the given. The offset (vertical blue lines) occurs at the highest point on the displacement curve for the given repetition. Two repetitions are analyzed in this figure.

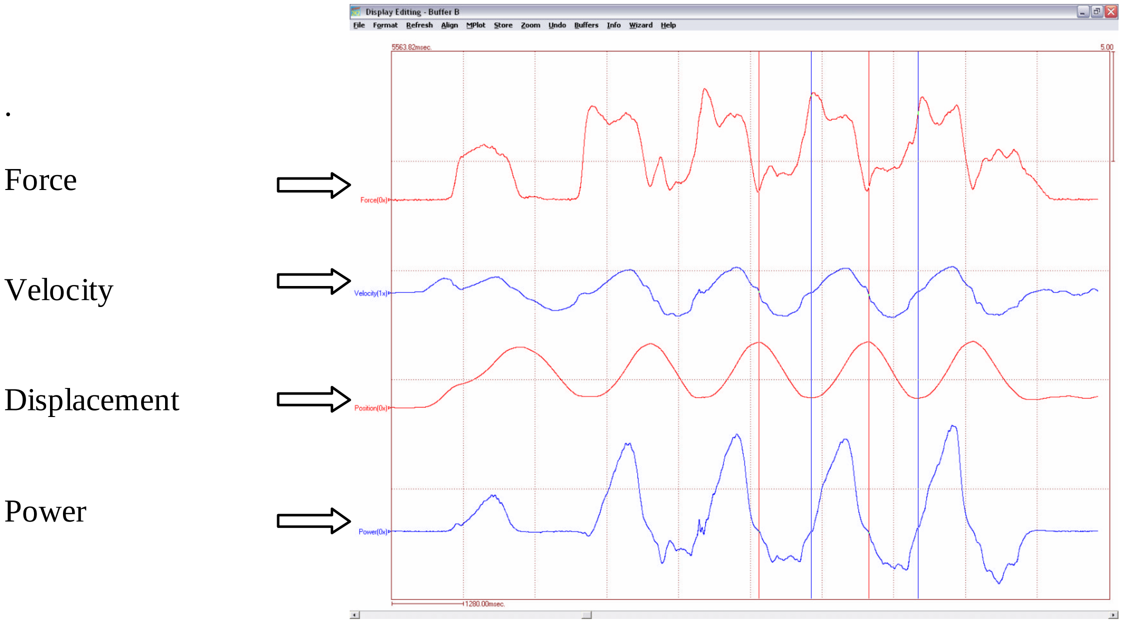


Figure 2 – The onset of the eccentric portion of the squat (vertical red lines) occurs at the highest point on the displacement curve for the given repetition. The offset (vertical blue lines) occurs at the lowest point on the displacement curve and at the exact point of the concentric onset for the given repetition. Two repetitions are analyzed in this figure.

Selection of the best repetition from each set to be used for analysis was based on the greatest concentric peak power. Each of the three FW reps from a set was considered for analysis, while only the final two reps were considered from the VC and SS trials. This is because the VC and SS movement started in the bottom position so only two full repetitions, defined as an eccentric movement followed by a concentric movement, were completed. Variables measured during both the concentric and eccentric movements were peak and mean values for force, velocity, power, impulse, and acceleration.

Statistical Methods

After selecting the best repetition from each set based on peak power, an average value for the two sets was calculated for each dependant variable. Subsequently, coefficieant of variation (CV) between the two testing sessions was calculated to measure precision and intraclass correlations (ICC) were calculated to assess stability reliability. Dependant variables with ICC>0.7 and CV<15% were considered reliable and were used for supsequent analysis. SPSS v14.0 was used for all data analysis. Two way AVOVAs were used to compare each of the Versa-Pulley™ cone conditions. A one-way ANOVA was used to compare all conditions (VP cone, VP straight shaft, free weights). Tukey post hoc analyses were conducted to determine where significant differences existed. Statistical significance was set at $p<0.05$.

Results

Concentric meaures of peak force (PF), mean force (XF), peak velocity (PV), mean velocity (XV), and mean power (XP) were all found to be reliable across all conditions (appendix D). Concentric peak power (PP) was reliable for all Versa-Pulley™ conditions but unreliable for the free weight conditions. Concentric acceleration and impulse measures were found to be unreliable, as well as all eccentric data. All 4kgCW data was also unreliable. Additionally, because peak measures of force, power, and velocity followed similar statistical trends to the average measure of these variables, only XF, XV, and XP will be discussed. Tables 2, 3 and 4 (appendix A) summarize XF, XV, and XP values for all Versa-Pulley™ conditions.

Figures 1-6 (appendix B) display comparisons between the VC conditions. XF was lower for 2kg/HighVel compared to 8kg/LowVel ($p<0.05$). XV was higher ($p<0.05$) than all other cone conditions for 2kg/HighVel. XV was lower ($p<0.05$) than all other cone conditions for

8kg/LowVel. XV for 2kg/LowVel and 8kg/HighVel were similar ($p>0.05$) but lower ($p<0.05$) than 2kg/HighVel and higher ($p<0.05$) than 8kg/LowVel. XP was equal across all VC conditions ($p>0.05$).

Figures 7-12 (appendix B) display comparison between VC and SS conditions. XF was similar for both the 2kg and 8kg SS conditions ($p>0.05$). However, both SS conditions produced greater XF than 2kg/HighVel, 2kg/LowVel, and 8kg/HighVel. 2kg/SS produced higher XV than 8kg/SS ($p<0.05$). 8kg/SS XV was lower than all other Versa-Pulley™ conditions ($p<0.05$). 2kg/SS XV was lower than all other Versa-Pulley™ settings except for 8kg/LowVel ($p<0.05$). 8kg/SS XP was lower than 2kg/LowVel and 8kg/LowVel ($p<0.05$).

Tables 5, 6, and 7 (appendix A) summarize XF, XV, and XP data for Versa-Pulley™ and free weight conditions. Figures 13-18 (appendix B) display comparisons between free weight and Versa-Pulley™ conditions. XF was higher with 85%1RM compared to 45%1RM. XF for 45%1RM was higher than 2kg/HighVel, 8kg/HighVel and 2kg/LowVel ($p<0.05$), XF for 65%1RM was greater XF values for all VC conditions ($p<0.05$) and XF for 85%1RM produced greater XF than all Versa-Pulley™ conditions ($p<0.05$). When comparing each of the free weight conditions, XV was greatest with 45%1RM and slowest with 85%1RM ($p<0.05$). 45%1RM produced lower XV , than 2kg/HighVel but higher XV than 8kg/LowVel, 2kg/SS, and 8kg/SS ($p<0.05$). 65%1RM produced lower XV than 2kg/HighVel, 2kg/LowVel, and 8kg/HighVel but higher XV than 8kg/SS ($p<0.05$). 85%1RM produced lower XV than 2kg/HighVel, 2kg/LowVel, and 8kg/HighVel ($p<0.05$). XP was similar for all free weight conditions ($p<0.05$). 8kg/SS XP was lower than all free weight conditions ($p<0.05$).

Discussion

Considering the abundance of comparisons between experimental conditions in this investigation, it is best to begin by comparing the VC conditions. XF values ranged from 495 newtons (N) to 801 N. The 8kg/LowVel condition was capable of producing higher XF than 2kg/HighVel, but the two intermediate conditions (8kg/HighVel and 2kg/LowVel) provided very comparable force values. Adding the straight shaft, however, increased XF values to levels greater than most of the cone conditions. It appears the only way to match the straight shaft force values with the comercially available Versa-Pulley™ is by using 8kg of counterweight and the low velocity pulley setting. This becomes most relevant when making comparisons with free wieght front squats. Only the straight shaft was capable of producing XF values equal to 65%1RM. When considering the Versa-Pulley™ configured with the cone shaft, XF values reached only as high as the 45%1RM free weight squats, and this was only accomplished using the 8kg/LowVel setting. None of the Versa-Pulley™ settings could match the XF output of 85% 1RM free weight front squats.

The VC conditions resulted in XVs ranging from 0.71m/s to 1.18m/s. The 2kg/HighVel condition produced the greatest XV while the 8kg/LowVel produced the slowest mean velocity. Similar XVs were observed for the 2kg/LowVel and 8kg/HighVel conditions. The straight shaft significantly lowered XVs to 0.61m/s (2kg) and 0.38m/s (8kg). Compared to free weight front squats (range = 0.54 -1.01 m/s), it appears that the Versa-Pulley™ is capable of matching velocities produced by a wide range of free weight front squat intensities (45-85% 1RM). Any desired XVs that would be observed using free weights can be achieved by simply manipulating the various settings on the Versa-pulley™. However, with the straight shaft installed, the higher end of the velocity spectrum is lost.

Interestingly, XP was similar across all VC conditions (591- 657 watts). Similar XP was also observed with the 2kg counterweight straight shaft condition (593 watts). However, when the large counterweights were added to the straight shaft, XP dropped to significantly to 400 watts. Thus, it appears that the commercially available Versa-Pulley™ configuration (cone shaft) could be considered an "iso-power" training device over the given ranges. More importantly, XP data obtained during VC front squats were statistically similar to XP data obtained during the free weight front squats. 2kg/SS also produced similar XP, but 8kg/SS produces XPs lower than all free weight conditions. Although all VC and free weight XP data was similar, it is important to note that calculated effect sizes were quite large between many conditions. Effect sizes for all data comparisons are seen in table 8. Effect sizes between all statistically insignificant comparisons ranged from 0.8 to 1.6. An effect size >0.8 is typically considered large. Comparisons with the 85% 1RM front squats resulted in relatively smaller effect sizes (0.1-0.6). Therefore, while most of the XP data was statistically similar, the large effect sizes suggest that using a larger sample size and different conditions may perhaps reveal important differences between Versa-Pulley™ and free weight power output.

The fact that the Versa-Pulley™ produces similar power output regardless which settings are used is very interesting. The power-velocity curve typically presents an inverted-U relationship but the Versa-Pulley™ seems to display a different trend. The Versa-Pulley™ does, however, follow the typical force-velocity relationship seen with other resistance training modalities where velocity decreases as load increases . The Versa-Pulley™ relationship between force, velocity, and power can be observed in figure 19. While it appears that the power produced using the Versa-Pulley™ stays the same regardless of the setting, an important question is whether this power is of appropriate magnitude. Compared to the traditional free weight front squats, there was no statistical difference between the Versa-Pulley™ and free weights with regard to mean power (excpet for 8kg/SS). However, the calculated effect sizes between the mean power data suggest that Versa-Pulley™ may produce power output ~20% less than traditional free weights, especially when considering lighter intensity free weight activities. While this may be the case, it is important to still consider the Versa-Pulley™ as a high power device. The front squat movement was used in this investigation because it is a full body movement and potentially very powerful, likely moreso than most exercises typically performed using the Versa-Pulley™ (rotational, upper body, etc). Many of these exercises can not be performed using free weights because they involve horizontal and rotaional movements where power and force levels would presumably be lower than during front squats. Therefore, since we probably observed more force and power during this investigation than would typically be observed during a Versa-Pulley™ workout, we would conclude that the Versa-Pulley™ is capable of producing adequte force and power for a typical training session.

There are a few methodolical points to consider with the investingation. Primarily, exercises used were somewhat unique for the participants. While all subjects were experienced with resistance training and had performed front squats in the past, the use of the shoulder harness was novel and was perceived as unusal for most participants. Additionally, all of the subjects were given only one day of familiarization. These factors could have produced greater variances in performance than what may have been observed with a longer period of familiarization. Furthermore, it is possible that a larger sample size could have increased the significance of some of the statistical measures.

Only mean measures of force, velocity, and power have been discussed in this paper since peak measures for these indices follow very similar patterns. However, all peak data can be observed in both tables (appendix A) and figures (appendix B).

In summary, the data from the present investigation indicates that the Versa-Pulley™ is capable of matching velocities experienced during traditional free weight exercise but may not be capable of producing the force and power experienced during most free weight intensities. This partially supports our first hypothesis as the kinematics were similar between free weights and the Vesa-Pulley™ but the kinetic characteristics differed. Our second, third, and fourth hypotheses were supported as the larger counterweights, low-velocity pulley setting, and straight shaft increased force and decreased velocity. The use of a straight shaft adds higher levels of force but this option is not currently available on the market. Our conclusions are summarized below.

Conclusions

- The Versa-Pulley™ produces less mean force than typical free weight training for the front squat.
- With the use of a straight shaft, force may be comparable to free weight front squats.
- The Versa-Pulley™ can match velocities observed during free weight front squats.
- Velocities are significantly reduced when a straight shaft is used.

- Versa-Pulley™ produces equal power (i.e., “isopower”) across all settings (may be slightly less than free weights for the front squat movement).
- The Versa-Pulley™ should be able to produced adequate force and power during typical Versa-Pulley™ exericses.

References

Berg, H. E., & Tesch, P. A. (1994). A gravity-independent ergometer to be used for resistance training in-space. *Aviation Space and Environmental Medicine, 65*(8), 752-756.

Appendix A – Tables

Table 1 – Descriptive characteristics (X±SE).

Variable	Group (n=11)
Age	24.7±0.9 yrs
Height	174.0±1.4 cm
Weight	79.8±2.4 kg

Table 2 – Mean force for Versa-Pulley™ Conditions (X±SE).

Condition	Mean Force(N)
2kg/HighVel	495.0 ± 30.7 * †
2kg/LowVel	627.6 ± 48.1 *
8kg/HighVel	612.5 ± 44.1 *
8kg/LowVel	801.7 ± 54.5
2kg/SS	883.6 ± 45.5
8kg/SS	962.0 ± 49.0

SS = straight shaft

* Sig. different from SS conditions.

† Sig. different from 8kg/LowVel ($p<0.05$).

Table 3 – Mean velocity for Versa-Pulley™ conditions (X±SE).

Condition	Mean Velocity (m/s)
2kg/HighVel	1.18 ± 0.05 *
2kg/LowVel	0.98 ± 0.04 †
8kg/HighVel	0.98 ± 0.06 †
8kg/LowVel	0.71 ± 0.04 *

* Sig. different from all other cone settings.

† Sig. different from 2kg/HighVel and 8kg/LowVel ($p<0.05$).

2kg/SS	0.61 ± 0.02 ‡
8kg/SS	0.38 ± 0.02 **

SS = straight shaft

** Sig. different from all other settings ($p<0.05$).

‡ Sig. different from all but 8kg/LowVel ($p<0.05$).

Table 4 – Mean Power for Versa-Pulley™ conditions (X±SE).

Condition	Mean Power (Watts)
2kg/HighVel	590.9 ± 48.4
2kg/LowVel	656.8 ± 54.2 *
8kg/HighVel	621.2 ± 50.1 *
8kg/LowVel	608.8 ± 53.3
2kg/SS	592.7 ± 39.3
8kg/SS	399.4 ± 26.7

SS = straight shaft

* Sig. different from 8kg/SS ($p<0.05$).

Table 5 – Mean force comparison between Versa-Pulley™ and free weight conditions (X±SE).

Condition	Mean Force(N)
2kg/HighVel	495.0 ± 30.7 * † ‡
2kg/LowVel	627.6 ± 48.1 * † ‡
8kg/HighVel	612.5 ± 44.1 * † ‡
8kg/LowVel	801.7 ± 54.5 † ‡
2kg/SS	883.6 ± 45.5 ‡
8kg/SS	962.0 ± 49.0 ‡
45% 1RM	874.7 ± 44.6 ‡
65% 1RM	1072.9 ± 40.4
85% 1RM	1228.3 ± 51.5 *

SS = straight shaft

* Sig. different from 45% 1RM ($p<0.05$).

† Sig. different from 65% 1RM ($p<0.05$).

‡ Sig. different from 85% 1RM ($p<0.05$).

Table 6 –Mean velocity comparison between Versa-Pulley™ and free weight conditions (X±SE)

Condition	Mean Velocity (m/s)
2kg/HighVel	1.18 ± 0.05 * $^{\dagger\ \ddagger}$
2kg/LowVel	0.98 ± 0.04 $^{\dagger\ \ddagger}$
8kg/HighVel	0.98 ± 0.06 $^{\dagger\ \ddagger}$
8kg/LowVel	0.71 ± 0.04 *
2kg/SS	0.61 ± 0.02 *
8kg/SS	0.38 ± 0.02 * †
45% 1RM	1.01 ± 0.03 $^{\dagger\ \ddagger}$
65% 1RM	0.77 ± 0.02 * ‡
85% 1M	0.54 ± 0.03 * †

SS = straight shaft

* Sig. different from 45% 1RM ($p<0.05$).

† Sig. different from 65% 1RM ($p<0.05$).

‡ Sig. different from 85% 1RM ($p<0.05$).

Table 7 – Mean Power for Versa-Pulley™ conditions (X±SE).

Condition	Mean Power (Watts)
2kg/HighVel	590.9 ± 48.4
2kg/LowVel	656.8 ± 54.2
8kg/HighVel	621.2 ± 50.1
8kg/LowVel	608.8 ± 53.3
2kg/SS	592.7 ± 39.3
8kg/SS	399.4 ± 26.7 * † ‡
45% 1RM	796.8 ± 54.8
65% 1RM	794.1 ± 39.3
85% 1M	674.1 ± 47.5

SS = straight shaft

* Sig. different from 45% 1RM (p<0.05).

† Sig. different from 65% 1RM (p<0.05).

‡ Sig. different from 85% 1RM (p<0.05).

Table 8 – Mean Power effect sizes between conditions ($d = M_1 - M_2 / \sigma$)

Condition	45%1RM	65%1RM	85%1RM
2kg/HighVel	1.3	1.6	0.5
2kg/LowVel	0.8	1.1	0.1
8kg/HighVel	1.1	1.3	0.3
8kg/LowVel	1.1	1.4	0.4
2kg/SS	1.6	1.5	0.6
8kg/SS	4.5	4.5	3.1

SS = straight shaft

Peak Data

Table 9 – Peak force for Versa-Pulley™ conditions (X±SE).

Condition	Peak Force (N)
2kg/HighVel	1113.9 ± 41.5
2kg/LowVel	1075.0 ± 56.9*
8kg/HighVel	1181.5 ± 60.9
8kg/LowVel	1256..2 ± 68.8
2kg/SS	1277.9 ± 46.6
8kg/SS	1400.2 ± 73.8

SS = straight shaft

* Sig. different from 8kg/SS ($p<0.05$)

Table 10 – Peak velocity for Versa-Pulley™ conditions (X±SE).

Condition	Peak Velocity (m/s)
2kg/HighVel	2.04 ± 0.10 *
2kg/LowVel	1.59 ± 0.07 †
8kg/HighVel	1.68 ± 0.11 †
8kg/LowVel	1.19 ± 0.07 *

* Sig. different from all other cone settings.

† Sig. different from 2kg/HighVel and 8kg/LowVel ($p<0.05$).

2kg/SS	1.11 ± 0.04 ‡
8kg/SS	0.71 ± 0.04 *

SS = straight shaft

** Sig. different from all other settings ($p<0.05$).

‡ Sig. different from all but 8kg/LowVel ($p<0.05$).

Table 11 – Peak Power for Versa-Pulley™ conditions (X±SE).

Condition	Mean Power (Watts)
2kg/HighVel	1579.4 ± 126.2*
2kg/LowVel	1410.2 ± 116.9
8kg/HighVel	1441.8 ± 107.4*
8kg/LowVel	1309.2 ± 109.8
2kg/SS	1371.1 ± 90.0
8kg/SS	926.7 ± 69.0

SS = straight shaft

* Sig. different from 8kg/SS ($p<0.05$).

Table 12 – Peak force comparison between Versa-Pulley™ and free weight conditions (X±SE).

Condition	Mean Force(N)
2kg/HighVel	1113.9 ± 41.5 † ‡
2kg/LowVel	1075.0 ± 56.9* † ‡
8kg/HighVel	1181.5 ± 60.9 † ‡
8kg/LowVel	1256..2 ± 68.8 ‡
2kg/SS	1277.9 ± 46.6 ‡
8kg/SS	1400.2 ± 73.8
45% 1RM	1382.5 ± 83.8
65% 1RM	1475.1 ± 71.6
85% 1RM	1622.2 ± 67.8

SS = straight shaft

* Sig. different from 45% 1RM ($p<0.05$).

† Sig. different from 65% 1RM ($p<0.05$).

‡ Sig. different from 85% 1RM ($p<0.05$).

Table 13-Peak velocity comparison between Versa-Pulley™ and free weight conditions (X±SE)

Condition	Mean Velocity (m/s)
2kg/HighVel	2.04 ± 0.10 * † ‡
2kg/LowVel	1.59 ± 0.07 ‡
8kg/HighVel	1.68 ± 0.11 † ‡
8kg/LowVel	1.19 ± 0.07 *
2kg/SS	1.11 ± 0.04 *
8kg/SS	0.71 ± 0.04 * † ‡
45% 1RM	1.59 ± 0.05 † ‡
65% 1RM	1.34 ± 0.04
85% 1M	1.09 ± 0.05 *

SS = straight shaft

* Sig. different from 45% 1RM ($p<0.05$).

† Sig. different from 65% 1RM ($p<0.05$).

‡ Sig. different from 85% 1RM ($p<0.05$).

Table 14 – Peak Power for Versa-Pulley™ conditions (X±SE).

Condition	Mean Power (Watts)
2kg/HighVel	1579.4 ± 126.2
2kg/LowVel	1410.2 ± 116.9
8kg/HighVel	1441.8 ± 107.4
8kg/LowVel	1309.2 ± 109.8
2kg/SS	1371.1 ± 90.0
8kg/SS	926.7 ± 69.0 * † ‡
45% 1RM	1459.5 ± 129.3
65% 1RM	1584.3 ± 75.2
85% 1M	1554.0 ± 108.3

SS = straight shaft

* Sig. different from 45% 1RM ($p<0.05$).

† Sig. different from 65% 1RM ($p<0.05$).

‡ Sig. different from 85% 1RM ($p<0.05$).

Appendix B – Figures

Figure 1 – Peak force comparison between the Versa-Pulley cone shaft conditions. No significant differences were observed (p>.05)

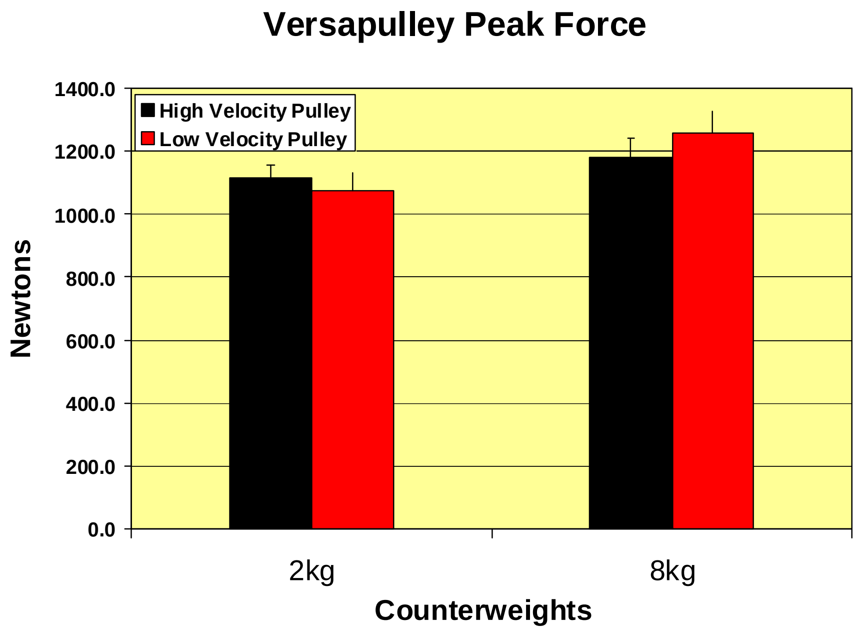
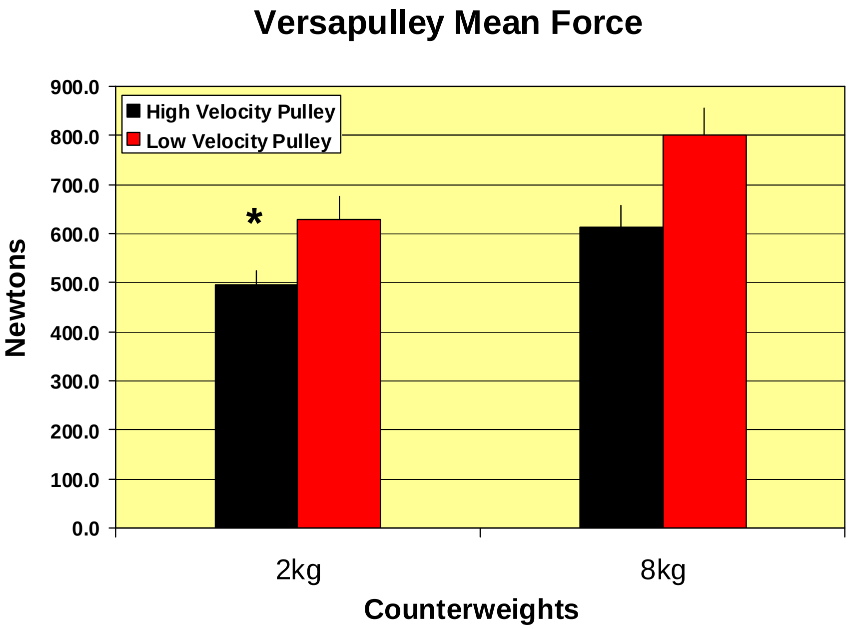
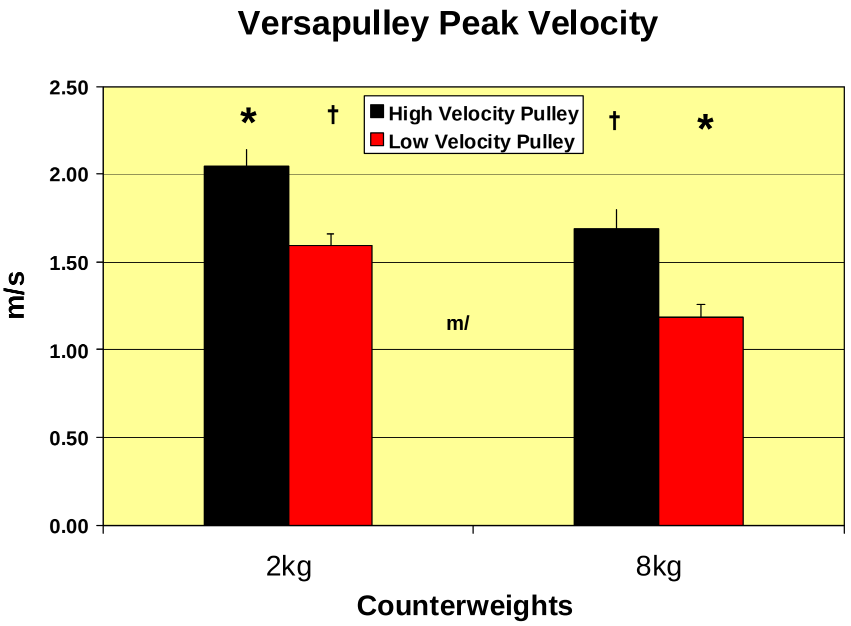


Figure 2 – Mean force comparison between the Versa-Pulley cone shaft conditions.



* Sig. different from 8kg/LowVel (p<0.05).

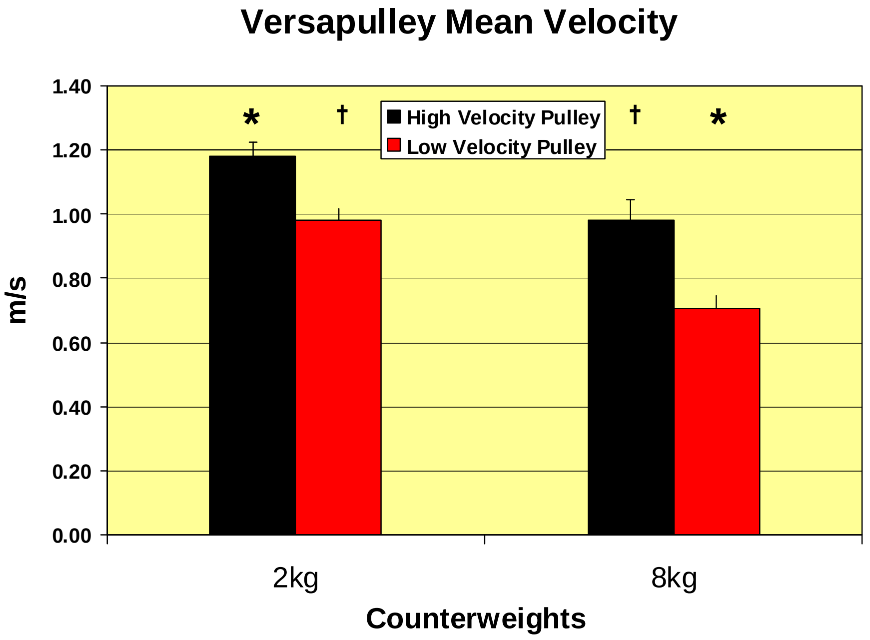
Figure 3 – Peak velocity comparison between the Versa-Pulley cone shaft conditions.



* Sig. different from all other settings ($p<0.05$).

† Sig. different from 2kg/HighVel and 8kg/LowVel ($p<0.05$).

Figure 4 – Mean velocity comparison between the Versa-Pulley cone shaft conditions.



* Sig. different from all other settings (p<0.05).

† Sig. different from 2kg/ HighVel and 8kg/LowVel (p<0.05).

Figure 5 – Peak power comparison between the Versa-Pulley cone shaft conditions. No significant differences were observed (p<.05).

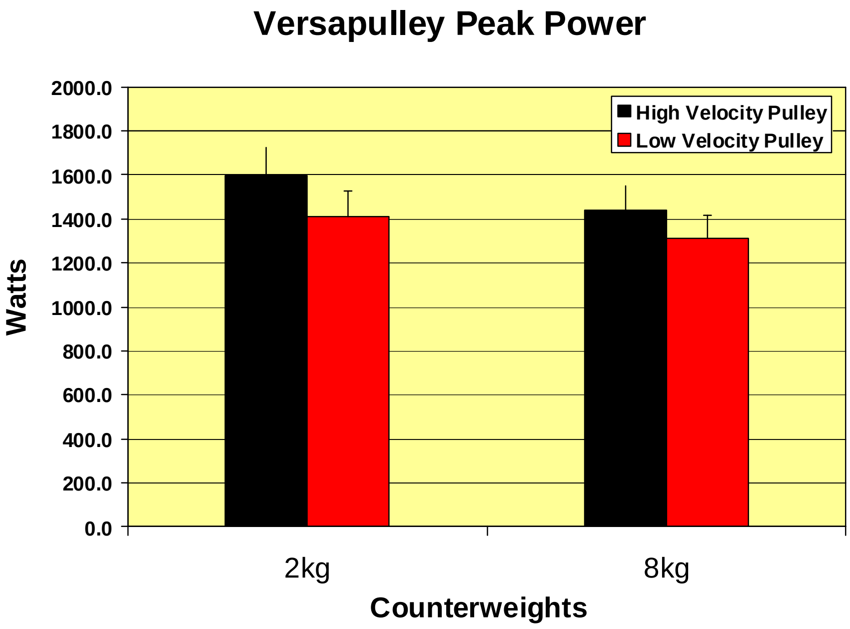


Figure 6 – Mean Power comparison between the Versa-Pulley cone shaft conditions. No significant differences were observed (p<.05).

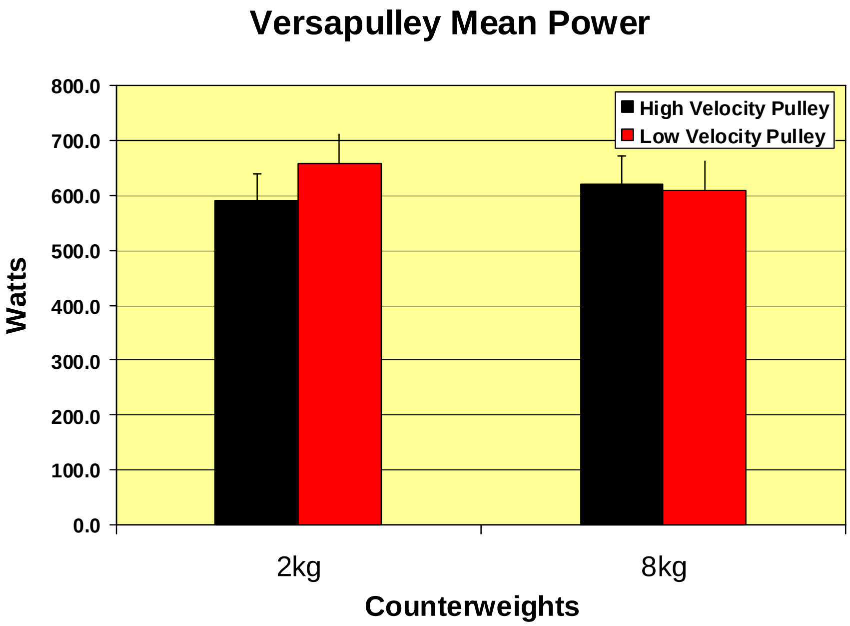
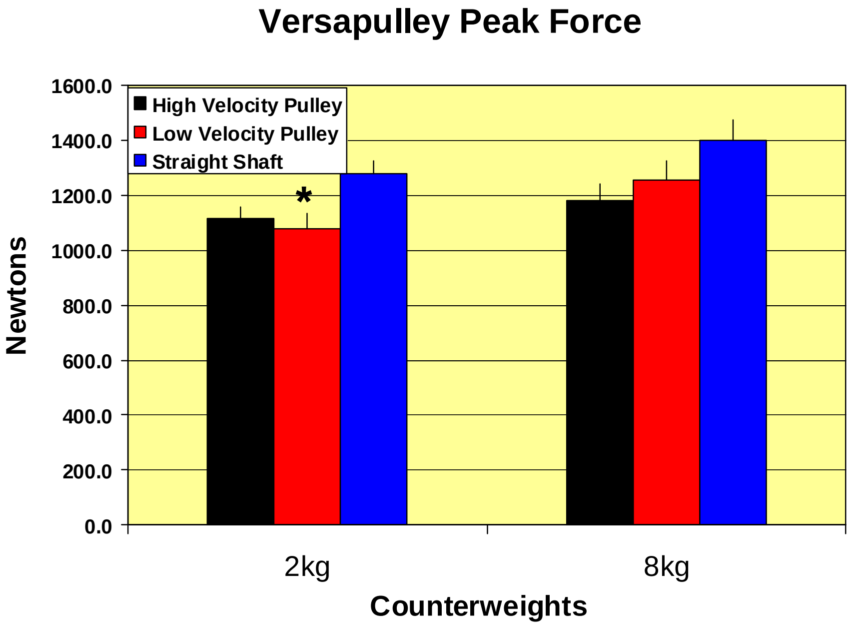
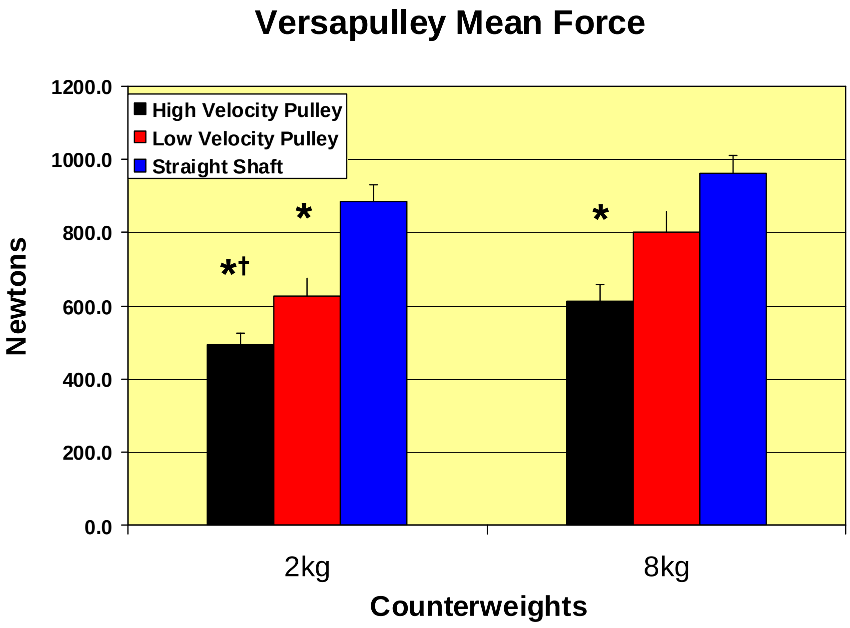


Figure 7 – Peak force comparison between the Versa-Pulley cone shaft and straight shaft conditions.



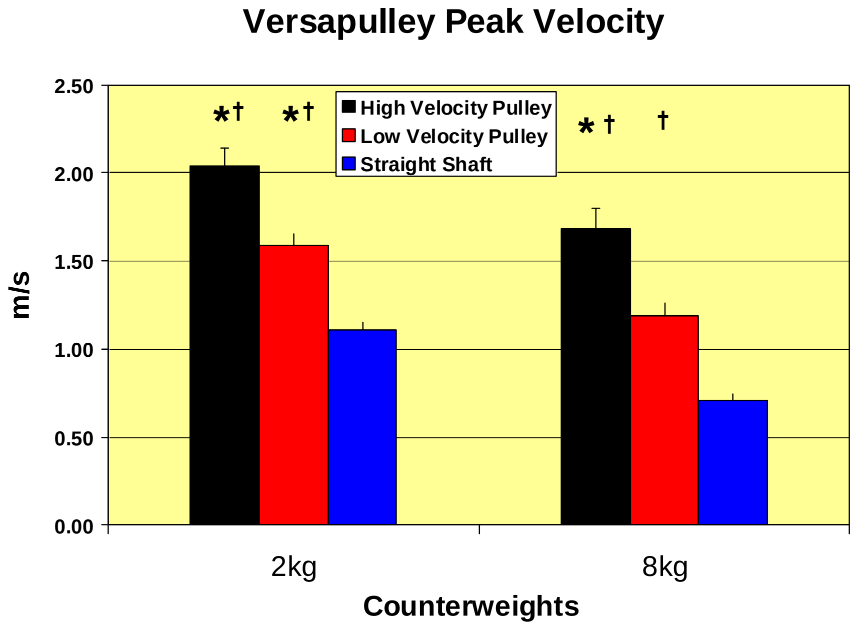
* Sig. different from straight shaft/LowVel ($p<0.05$).

Figure 8 – Mean force comparison between the Versa-Pulley cone shaft and straight shaft conditions.



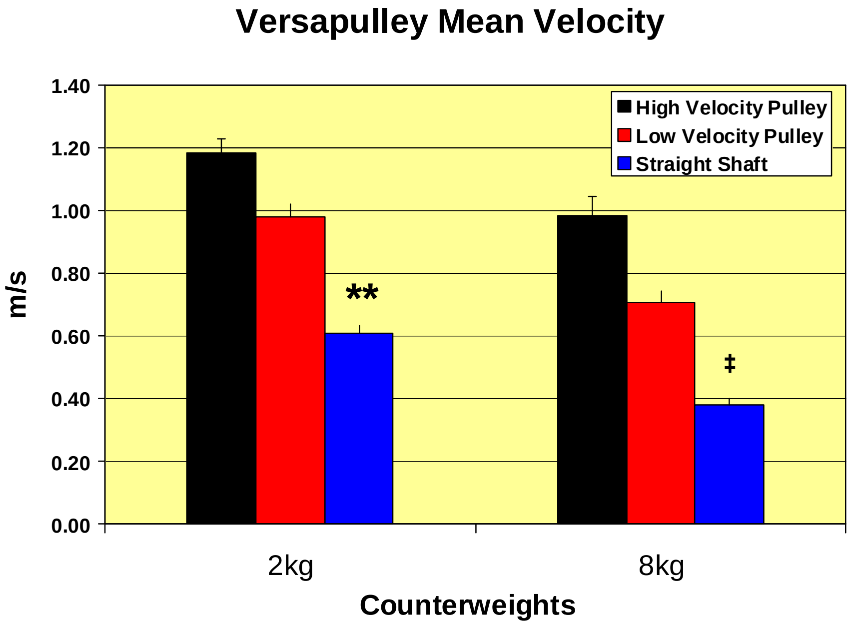
* Sig. different from straight shaft (p<0.05).
† Sig. different from 8kg/LowVel (p<0.05).

Figure 9 – Peak velocity comparison between the Versa-Pulley cone shaft and straight shaft conditions.



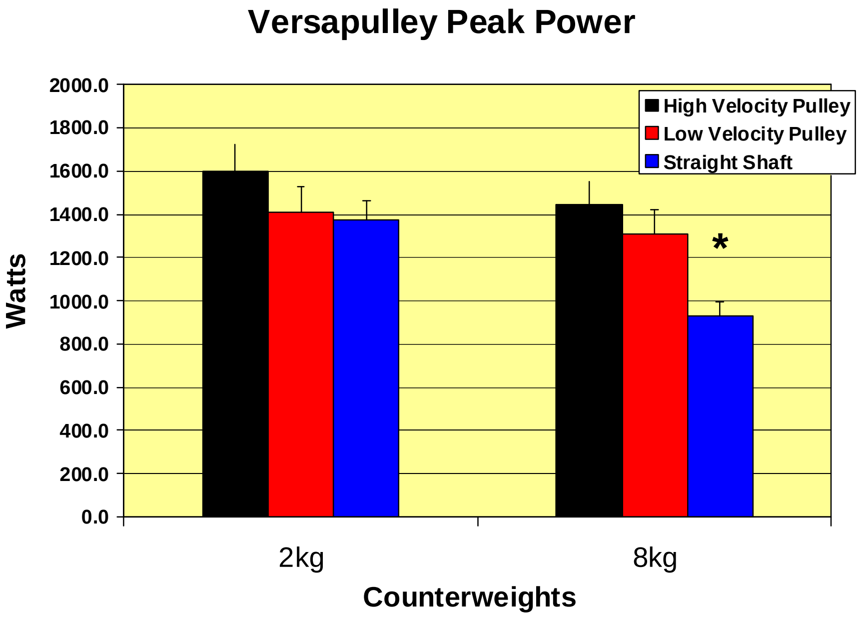
* Sig. different from 2kg/straight shaft (p<0.05).
† Sig. different from 8kg/straight shaft (p<0.05).

Figure 10 – Mean velocity comparison between the Versa-Pulley cone shaft and straight shaft conditions.



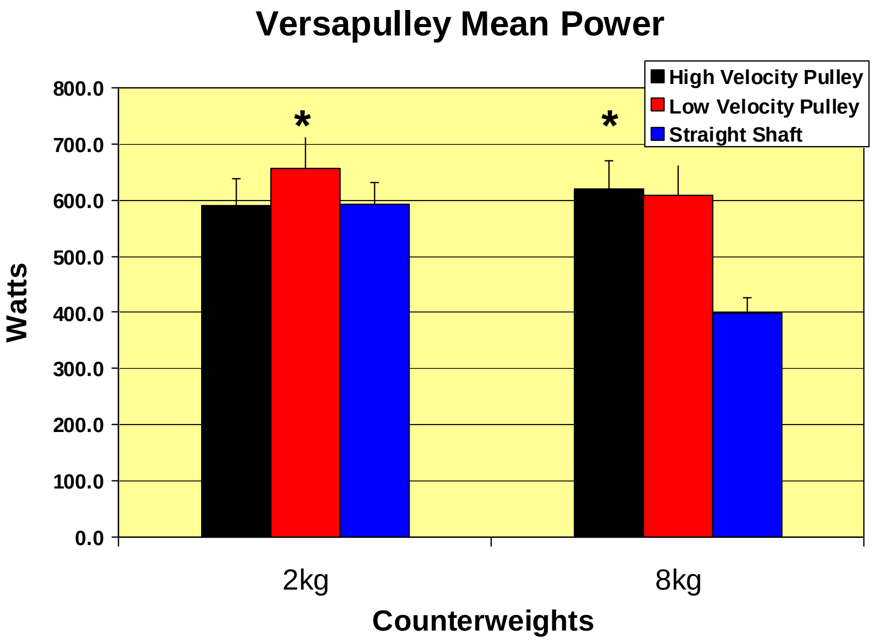
** Sig. different from all other settings (p<0.05).
‡ Sig. different from all but 8kg/LowVel (p<0.05).

Figure 11 – Peak power comparison between the Versa-Pulley cone shaft and straight shaft conditions.



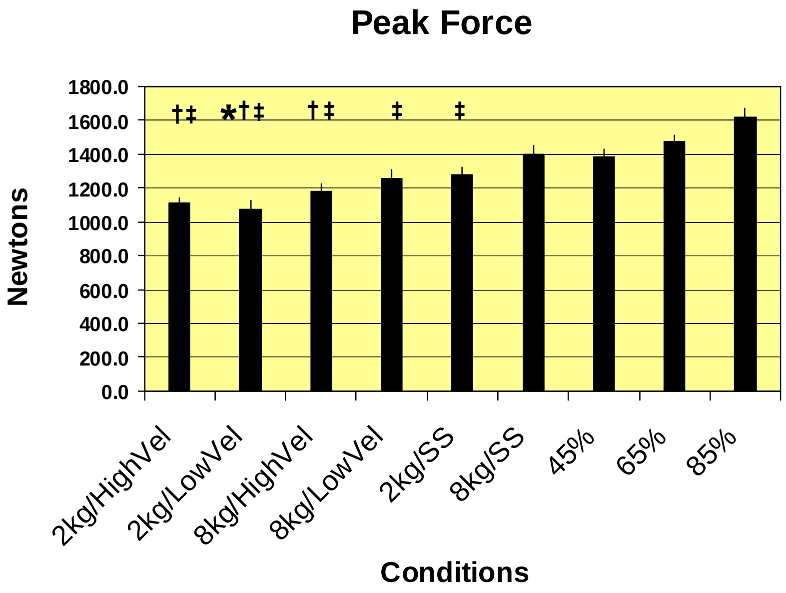
* Sig. different from all other settings (p<0.05

Figure 12 – Mean power comparison between the Versa-Pulley cone shaft and straight shaft conditions.



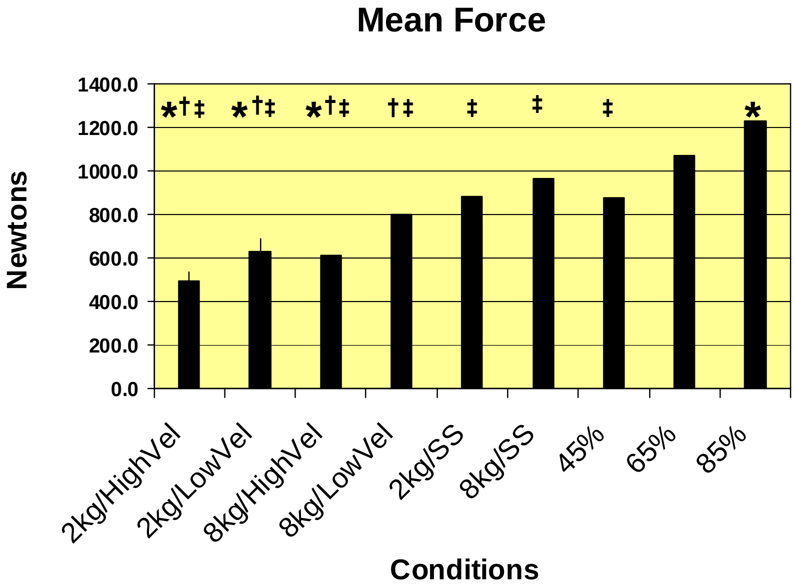
* Sig. different from 8kg/SS ($p<0.05$).

Figure 13 – Peak force comparison between the Versa-Pulley conditions and free weight conditions.



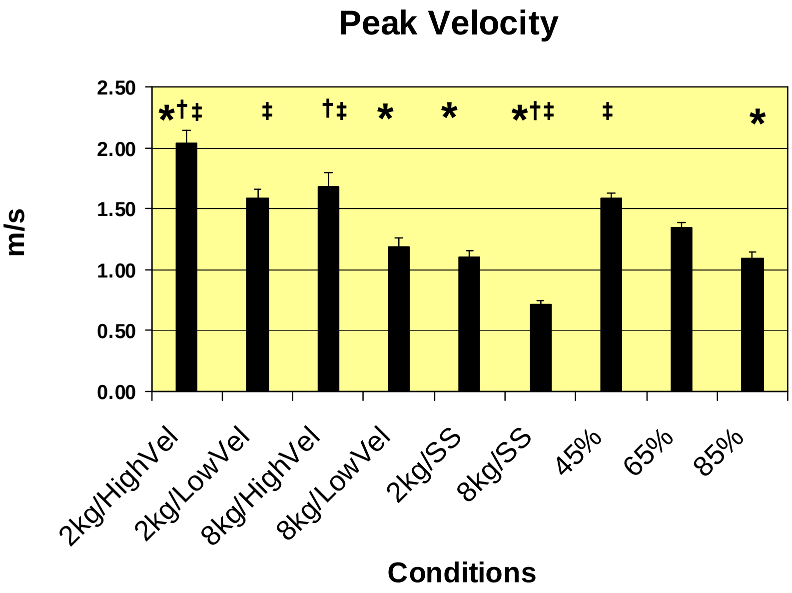
* Sig. different from 45%1RM ($p<0.05$).
† Sig. different from 65%1RM ($p<0.05$).
‡ Sig. different from 85%1RM ($p<0.05$).

Figure 14 – Mean force comparison between the Versa-Pulley conditions and free weight conditions.



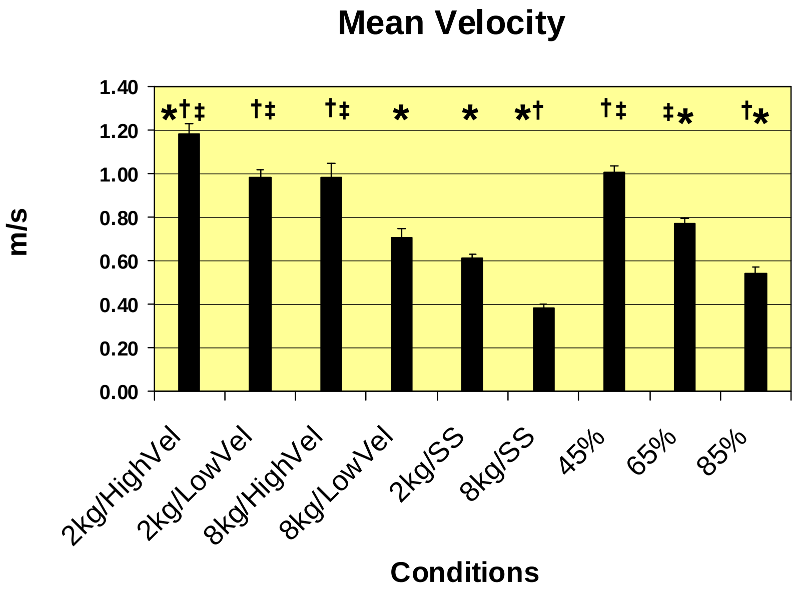
* Sig. different from 45%1RM (p<0.05).
† Sig. different from 65%1RM (p<0.05).
‡ Sig. different from 85%1RM (p<0.05).

Figure 15 – Peak velocity comparison between the Versa-Pulley conditions and free weight conditions.



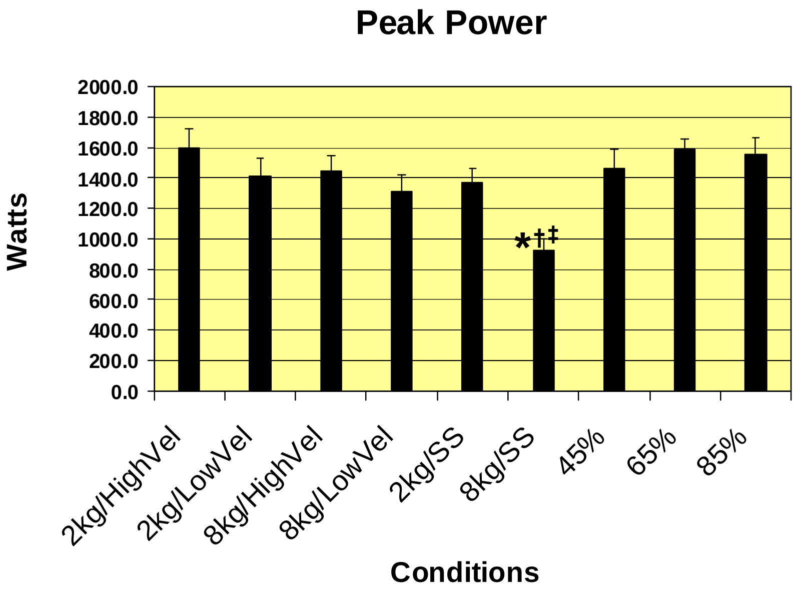
* Sig. different from 45%1RM ($p<0.05$).
† Sig. different from 65%1RM ($p<0.05$).
‡ Sig. different from 85%1RM ($p<0.05$).

Figure 16 – Mean velocity comparison between the Versa-Pulley conditions and free weight conditions.



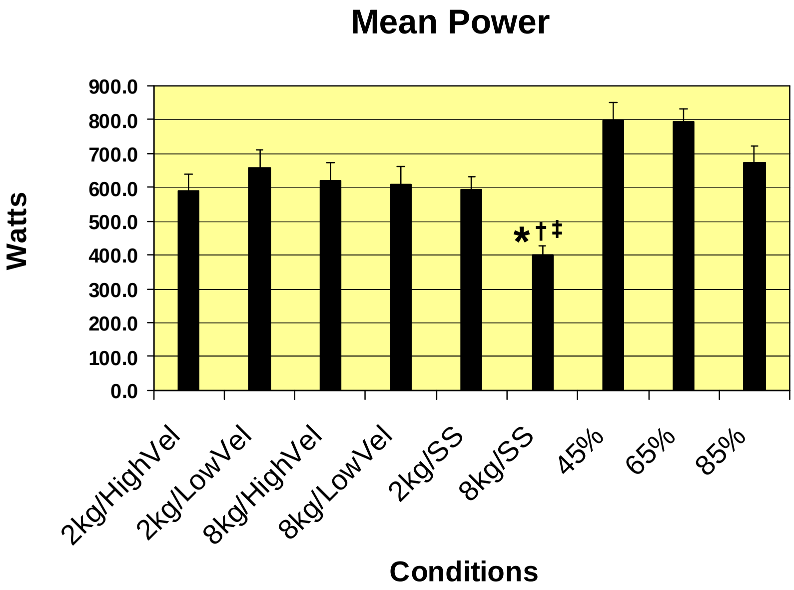
* Sig. different from 45%1RM ($p<0.05$).
† Sig. different from 65%1RM ($p<0.05$).
‡ Sig. different from 85%1RM ($p<0.05$).

Figure 17 – Peak power comparison between the Versa-Pulley conditions and free weight conditions.



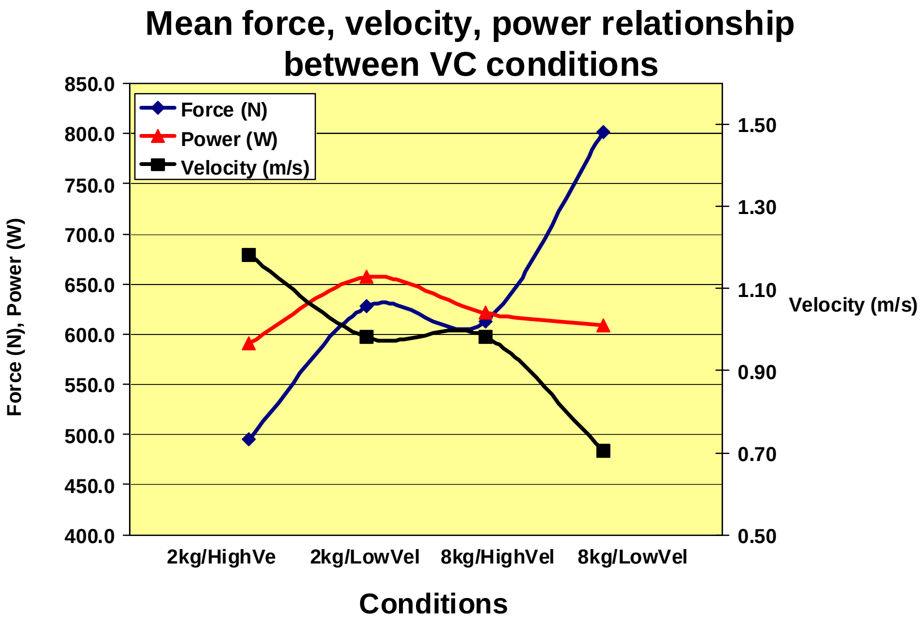
* Sig. different from 45%1RM ($p<0.05$).
† Sig. different from 65%1RM ($p<0.05$).
‡ Sig. different from 85%1RM ($p<0.05$).

Figure 18 – Mean power comparison between the Versa-Pulley conditions and free weight conditions.



* Sig. different from 45%1RM (p<0.05).
† Sig. different from 65%1RM (p<0.05).
‡ Sig. different from 85%1RM (p<0.05).

Figure 19 – Mean force, velocity and power relationship between Versa-Pulley cone conditions. Notice the constant power between all conditions.



Appendix C – Photographs

Photo 1 - Shoulder harness used for both free weight and Versa-Pulley front squats.

Photo 2 - Free weight front squats performed on force platform with linear velocity transducer (red line) attached.

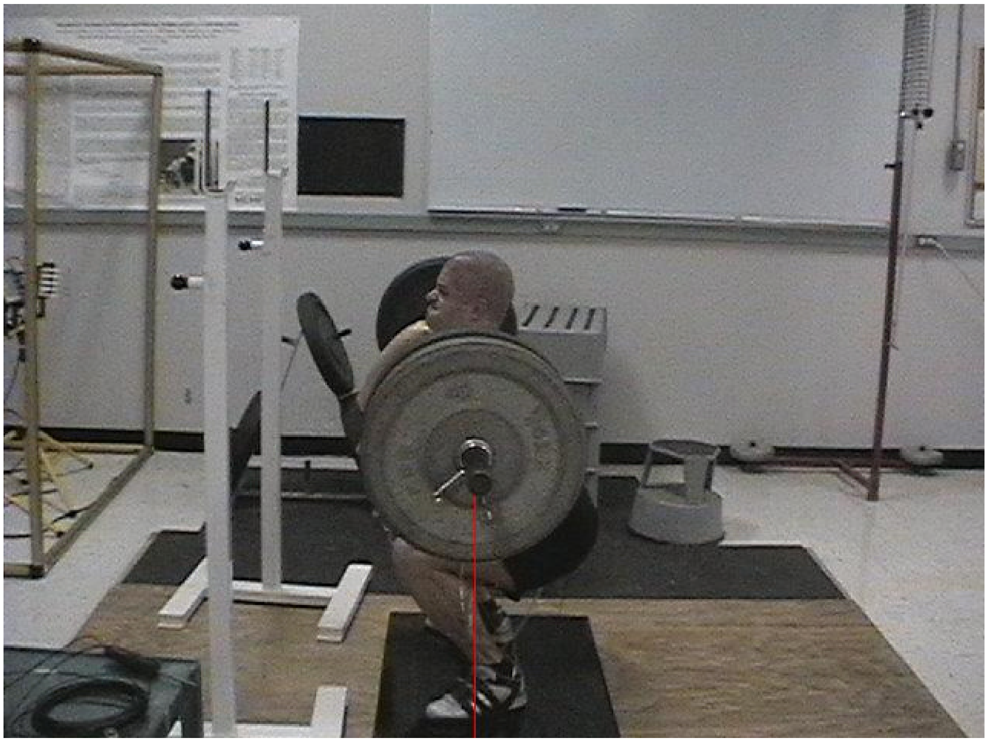


Photo 3 – Configuration for Versa-Pulley front squats. Velocity transducer (red line) is attached the shoulder harness at level of the sternum. Linear force transducer (arrow) is attached in line with tether via two carabiners.

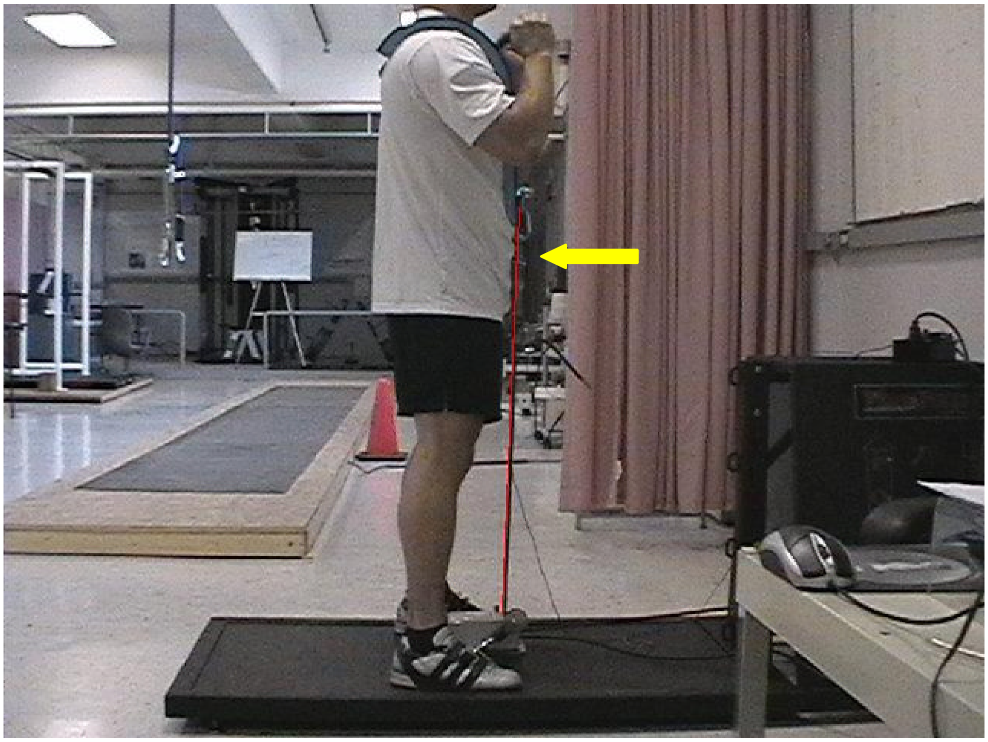
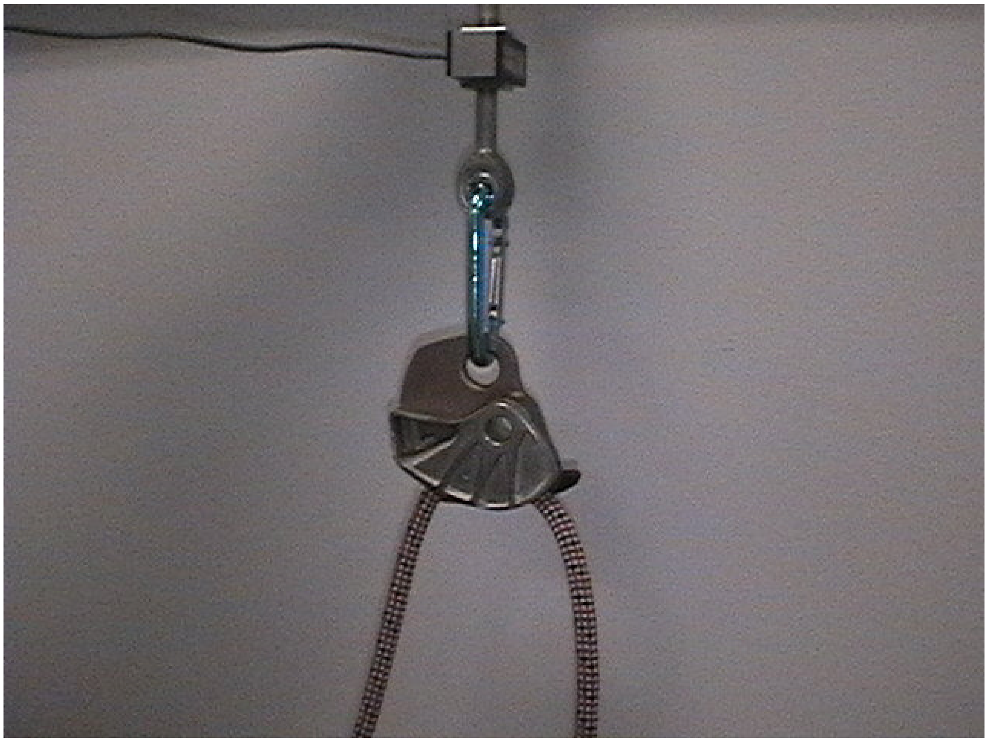


Photo 4 – Versa-Pulley configuration during front squat movement.

Photo 5 – Adjustable pulley using to attach tether to force tranducer and to adjust length of tether.



Appendix D –Reliability Data

Reliability Table 1 – Reliability data for Versa-Pulley Cone shaft.

Variable	1 large		5 large		1 medium		5 medium		1 small		5 small	
	ICC	**CV**	**ICC**	**CV**	**ICC**	**CV**	**ICC**	**CV**	**ICC**	**CV**	**ICC**	**CV**
CPF	0.9	6.5	0.7	12.2	0.2	11.9	0.7	7.9	0.9	5.0	0.7	9.7
CXF	0.8	11.8	0.8	10.8	0.4	16.3	0.4	15.5	0.7	11.6	0.8	10.2
CPV	0.5	14.4	0.8	9.9	0.6	10.5	0.5	14.9	0.9	5.1	0.8	6.3
CXV	0.9	8.4	0.8	9.2	0.4	12.2	0.4	12.8	0.8	5.3	0.8	7.6
CPP	0.7	13.0	0.7	21.4	0.2	15.1	0.7	15.4	0.7	13.3	0.8	13.3
CXP	0.9	9.5	0.9	11.8	0.6	18.7	0.5	56.4	0.7	13.6	0.9	8.6
EPF	0.5	28.3	0.8	24.0	0.3	17.5	0.4	29.6	0.8	10.8	0.7	20.0
EXF	0.8	18.8	0.8	28.3	0.5	21.4	0.3	26.6	0.8	13.4	0.7	20.4
EPV	0.6		0.8		0.7		0.5		0.9		0.8	
EXV	0.4		0.6		0.9		0.5		0.6		0.6	
EPP	0.3		0.7		0.5		0.3		0.4		0.4	
EXP	0.8		0.6		0.7		-0.1		0.8		0.9	
CI	0.9	8.5	0.1	29.6	0.0	18.4	0.0	24.5	0.8	4.4	0.7	9.7
EI	0.8	19.0	0.5	38.2	0.5	18.9	0.5	27.8	0.4	16.9	0.7	23.8
TI	0.9	9.2	0.3	29.7	0.2	18.2	0.2	23.2	0.7	7.9	0.7	13.2
CPA	0.6	30.9	0.0	72.3	0.7	40.3	0.0	49.4	0.6	35.6	0.6	80.0
CXA	0.8	262.2	0.3	105.9	-0.1	169.2	-0.2	468.5	0.0	283.5	-0.2	192.3
EPA	0.7		0.5		0.6		0.1		0.8		0.3	
EXA	-0.3		0.8	318.8	0.0	374.7	-0.1		0.5	177.0	-0.2	

Reliability Table 2 – Reliability data for Versa-Pulley straight shaft.

Variable	small		medium		large	
	ICC	**CV**	**ICC**	**CV**	**ICC**	**CV**
CPF	0.7	7.6	0.8	8.7	0.8	8.4
CXF	0.9	8.1	0.9	8.7	0.9	11.3
CPV	0.9	4.9	0.9	5.6	0.9	5.2
CXV	0.8	6.6	0.6	9.3	0.7	8.7
CPP	0.8	11.7	0.9	11.1	0.9	10.0
CXP	0.9	6.4	0.9	8.1	0.9	12.1
EPF	0.7	26.0	0.7	36.8	0.8	39.8
EXF	0.6	43.6	0.6	48.9	0.6	68.8
EPV	0.5		0.8		0.7	
EXV	0.7		0.4		0.5	
EPP	0.3		0.6		0.4	
EXP	0.7		0.8		0.7	
CI	0.5	10.8	0.6	11.2	0.5	14.6
EI	0.4	50.3	0.4	61.9	0.4	82.7
TI	0.4	17.8	0.5	19.5	0.4	25.3
CPA	0.1	37.9	-0.2	57.5	0.4	41.6
CXA	-0.1	179.3	0.4	112.8	-0.7	135.1
EPA	0.6		0.8		0.4	
EXA	-0.2		-0.1		0.1	41.4

Reliability Table 3 – Reliability data for Versa-Pulley free-weights

Variable	45		65		85	
	ICC	CV	ICC	CV	ICC	CV
CPF	0.9	6.0	0.9	5.6	0.9	6.5
CXF	0.7	6.9	0.9	2.9	1.0	2.6
CPV	0.6	5.9	0.6	5.9	0.7	10.3
CXV	0.8	4.1	0.8	6.1	0.8	6.4
CPP	0.634	15.200	0.555	11.500	0.514	19.900
CXP	0.6	11.2	0.8	8.7	0.9	7.9
EPF	0.9	8.2	0.9	5.7	0.9	4.0
EXF	0.9	6.2	0.9	4.1	1.0	1.9
EPV	0.8		0.7		0.8	
EXV	0.8		0.7		0.9	
EPP	0.8		0.8		0.9	
EXP	0.9		0.8		0.9	
CI	0.8	6.2	0.9	5.1	0.9	6.3
EI	0.8	8.1	0.6	11.0	0.7	7.0
TI	0.9	5.8	0.8	6.7	0.9	5.2
CPA	0.6	5.9	0.6	6.0	0.7	10.2
CXA	0.8	4.1	0.7	6.1	0.8	6.4
EPA	0.3		0.1		-0.4	
EXA	0.8		0.7		0.9	