International Journal of Occupational Safety and Ergonomics (*JOSE*) 2009, Vol. 15, No. 3, 255–263

Understanding the Effect of Speed of Exertion on Isokinetic Strength Using a Multiaxial Dynamometer

Ashish D. Nimbarte
Fereydoun Aghazadeh
Sai Chaitanya R. Bogolu

Department of Construction Management and Industrial Engineering, Louisiana State University, Baton Rouge, USA

Sudhakar L. Rajulu

NASA's Johnson Space Center, Houston, TX, USA

In this study a multiaxial isokinetic dynamometer was used to measure strength during various upper-body isokinetic exertions. Ten male participants performed 7 different upper-body isokinetic exertions. In addition, to evaluate the effect of speed on strength, each participant performed sitting pull exertions at the speed of 0.026, 0.130, and 0.260 m/s. Average isokinetic strength increased from 236.6 ± 39.1 to 291.8 ± 65.8 N with the initial increase in speed from 0.026 to 0.130 m/s. The average isokinetic strength decreased to 276.7 ± 87.2 N with a further increase in speed to 0.260 m/s. The curve between isokinetic strength and speed followed a bell-shaped curve (fitted with the Gaussian function, $R^2 = .9$*). The results of this study could be useful in deciding on the work pace of various manual material handling tasks requiring maximal and/or near maximal exertions.*

isokinetic strength fatigue repetitions

1. INTRODUCTION

Upper-body strength is frequently required for performing manual material handling (MMH) tasks in both industrial and domestic environments [1]. It is important to know the strength of humans under different exertion scenarios to match their capabilities with different types of tasks. The knowledge of workers' strength is also very important in designing equipment and tools to improve the human–work interface [2]. This knowledge could also be used to design and develop engineering guidelines. Tasks or equipment designed without such guidelines having been followed could overload the muscle–tendon–bone–joint system causing injuries [3].

Strength is defined as a measure of humans' physical capabilities that permit humans to exert force or sustain external loading without inflicting personal injury [4]. Strength can be measured during static and dynamic exertions. During the former, both the body segments and the object upon which the forces are applied remain stationary. Static strength is defined as the capacity of the muscle to produce force or torque with a single maximal voluntary isometric exertion [2, 5]. In the past, much research focussed on understanding the behavior of static strength

---

Correspondence and requests for offprints should be sent to Fereydoun Aghazadeh, 3128 Patrick F. Taylor Hall, Louisiana State University, Baton Rouge, LA 70802-6409, USA. E-mail: <aghazadeh@lsu.edu>.

with respect to time [6, 7, 8, 9, 10]. In Caldwell's study, participants performed maximum pull exertion for 70 s [11]. The results showed that strength decreased linearly with the time. Garg, Hegmann, Schwoerer, et al. studied endurance time as a function of maximum voluntary contraction (MVC) [12]. Endurance time was defined as the maximum amount of time a subject could continuously hold a given weight in a specified posture. Endurance time was found to decrease nonlinearly with an increase in %MVC.

Dynamic strength during moderately frequent lifting tasks (up to once per minute) was proposed as a better screening tool than the use of maximal isometric strength [4]. Dynamic exertions can be isotonic, isokinetic or isoinertial. Isotonic exertion involves applying force with muscular tension constant throughout the range of motion. Isokinetic strength involves force application against resistance at a constant rate of movement. Isoinertial strength is the measure of a person's ability to overcome initial static resistance by measuring the maximum weight the person can handle and move to an assigned point at freely chosen speed [2, 4]. In the industrial environment, MMH tasks have to be performed repetitively at a fast pace. It is crucial that the tasks requiring maximal or near maximal exertions be performed smoothly at uniform speed without jerking; hence, isokinetic strength is often measured. According to Mital, Channaveeraiah, Fard, et al. repetitive dynamic strength is a more accurate measure of an individual's lifting capacity for frequently performed tasks than maximal static or dynamic strength [13]. In this study strength during various upper-body isokinetic exertions was measured with a multipurpose, multiaxial isokinetic dynamometer (MMID), and the effect of different exertion speeds on the isokinetic pull strength over fixed duration was evaluated.

2. METHODS

2.1. Subjects

Ten male employees of NASA's Johnson Space Centre, Houston, TX, USA, volunteered to participate in this study. The average age, height, and weight of the participants were 37.7 ± 10.3 years, 178.1 ± 6.1 cm, and 82.5 ± 15.5 kg, respectively.

2.2. Equipment

Isokinetic dynamic strength was measured with an MMID at the anthropometry and biomechanics facility at NASA's Johnson Space Center (Figure 1). The MMID is a cable-

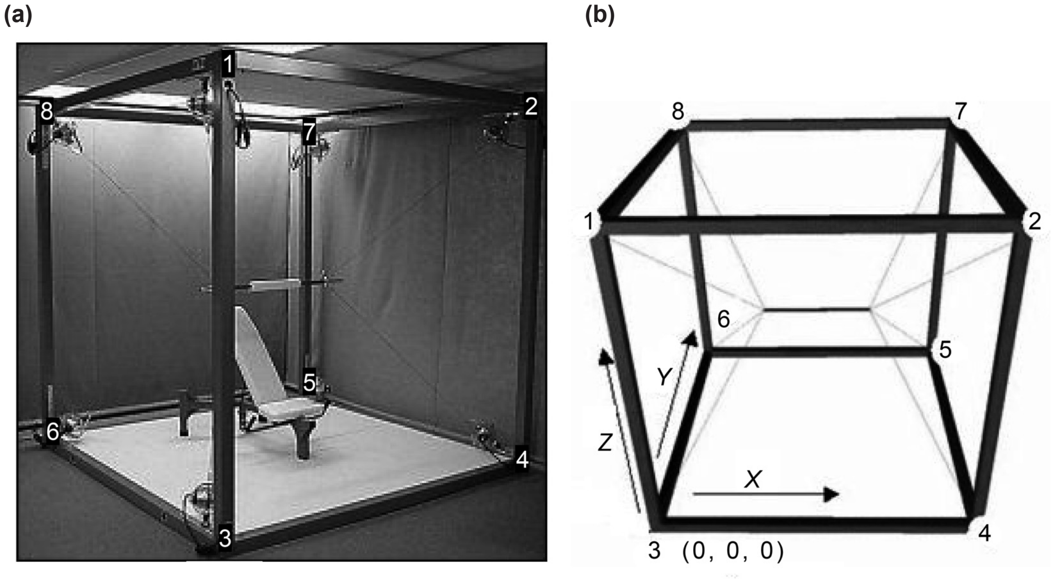

Figure 1. (a) Multiaxial isokinetic dynamometer (MMID) system configuration, (b) representative cubic configuration with the co-ordinate system.

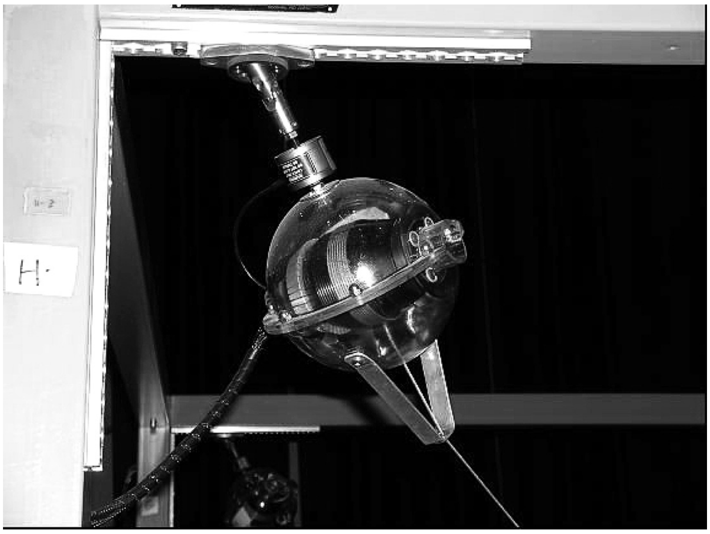

Figure 2. A module (pod).

driven electromechanical system that can generate and measure both position and force with 6 *df* simultaneously along any path. The dynamometer is primarily used for measuring and stressing muscles in the arms, legs, and trunk. The MMID was originally developed for NASA as a potential exercise system for astronauts. The extremely large operational volume of the MMID can accommodate movements of both upper and lower limbs. A simple bar serves as the manipulandum or effector bar. Eight cables from the active modules (pod) are attached to the effector bar, four on each end. This configuration makes a comfortable balance between a range of motions and force generating capability possible. The eight active modules are the key components of the MMID (Figure 2). They house a brushless DC motor, encoder, harmonic drive, cable take-up reel, and all other mechanical components. The modules reel in or spool out the cable in unison to achieve a desired trajectory of the effector bar. With all the modules maintaining a given position, the effector bar can be rigidly fixed in space. The MMID is capable of achieving complex, 6 degree-of-freedom motions by using all the active modules.

The MMID is capable of measuring forces as high as 1 334.46 N, depending on the geometrical configuration. The system can be easily configured to any number of conventional and additional exercises. A graphical user interface on the host computer controls the position and the motion of the effector bar.

2.3. Data Collection

The MMID data output comprised of a real-time position of the effector bar in the *X*, *Y*, *Z* axes; forces, speed, acceleration, deceleration, and the moment values. The *X* axis was the axis in the frontal and horizontal transverse plane. The *Y* axis was the axis in the sagittal and horizontal transverse plane. The *Z* axis was the axis in the sagittal plane. Strength data was collected at 60 Hz. The speed of the effector bar (i.e., the speed at which it could be moved) was set to 0.260 m/s during all upper-body exertions. The participants were instructed to move the effector bar by pushing, pulling, raising, etc., without jerking it. They were told to build the speed and force gradually. Each participant performed 6–7 repetitions. Three of the highest strength values during each repetition were determined. These values were then averaged to calculate the maximum strength for that repetition. If the strength values obtained during the first 3 repetitions were not within 10% of one another, the 4th repetition was analyzed and three closest values were determined. They were then averaged to find the maximum strength during that exertion. A rest period of 3–4 min was allowed between the different types of exertions.

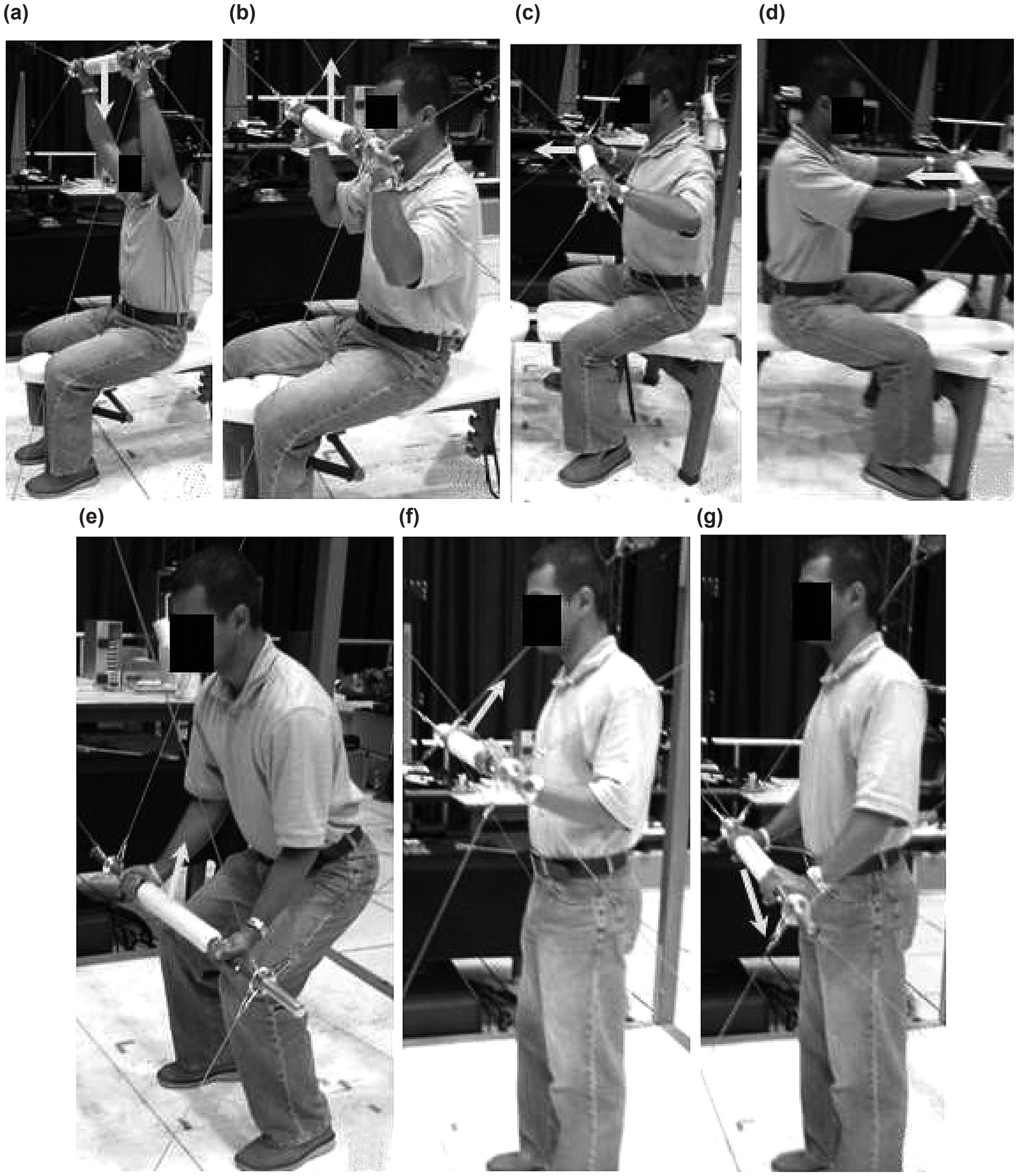

Figure 3. Starting body postures during various upper-body exertions: (a) sitting lateral pull down, (b) sitting military press, (c) sitting push, (d) sitting pull, (e) open hatch, (f) standing curl, (g) standing triceps press. *Notes.* Arrows show the direction of motion.

Maximum isokinetic strength was determined during seven different routines: (a) sitting lateral pull down, (b) sitting military press, (c) sitting push, (d) sitting pull, (e) open hatch, (f) standing curl, and (g) standing triceps press. Figure 3 presents the approximate starting body postures for each routine. Prior to the actual data collection, the participants tried each upper-body exertion a few times to become familiar with it. To better visualize the different upper-body exertions, the specifics of effector bar motions, speed, acceleration, and the trigger level for one participant are presented in Table 1. During the sitting lateral pull down and sitting military press routine the motion of the effector bar ranged between 1.68 and 1.22 m in the sagittal plane.

During the sitting push and pull routine, the motion of the effector bar ranged between 0.92 and 1.60 m, and 1.60 and 0.92 m, respectively, in the horizontal transverse plane. The range of motion of the effector bar in the sagittal plane for the open hatch, standing curl, and standing triceps press was 0.66–1.68, 0.99–1.35, and 1.35–0.99 m, respectively.

TABLE 1. Specifications of Routines

	Position (m)		
Strength Tests	***X* axis**	***Y* axis**	***Z* axis**
Sitting lateral pull down	1.17	1.25	1.68–1.22
Sitting military press	1.17	1.37	1.68–1.22
Sitting push	1.17	0.92–1.60	1.17
Sitting pull	1.17	1.60–0.92	1.17
Open hatch	1.17	1.17	0.66–1.68
Standing curl	1.17	1.17	0.99–1.35
Standing triceps press	1.17	1.17	1.35–0.99

Notes. In all tests, speed = 0.260 m/s, trigger level = 44.49 N.

The effect of different exertion speeds on isokinetic strength was studied during the sitting pull exertion at 0.026, 0.130, and 0.260 m/s (1, 5, 10 in./s). The participants performed sitting pull exertion (Figure 4) for 400 s at each speed. The order of the experimental trials was randomized. A slight variation in the total number of repetitions performed over 400 s was observed. To determine the average strength values, the number of repetitions was made constant for all subjects. For this purpose, the lowest number of repetitions among all the participants during each exertion speed was determined and the repetitions were set to that number. For example, if one participant had 14 repetitions, which was the lowest number among all the participants at 0.026 m/s, the number of repetitions for this exertion speed was set to 14. Likewise, the number of repetitions for the exertion speeds of 0.130 and 0.260 m/s was set to 43 and 53, respectively.

3. RESULTS

3.1. Maximum Isokinetic Srength

Table 2 reports the maximum isokinetic strength of all the participants for various upper-body exertions. The strength values are reported for axes along the sagittal and horizontal transverse plane (F_Y) and the sagittal plane (F_Z). Along the F_Y axis, the highest strength of 353.85 ± 62.89 N was found during the sitting pull exertion and the lowest of 78.82 ± 28.11 N during the triceps press exertion. Along F_Z, the highest strength of 599.48 ± 75.84 N was found during the sitting lateral pull exertion and the lowest of 97.86 ± 23.62 N during the sitting pull exertion.

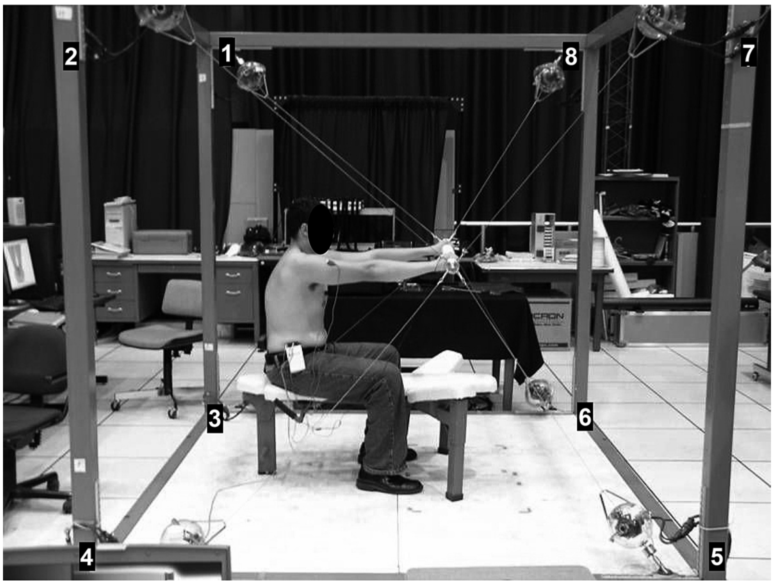

Figure 4. A participant performing a pull routine.

TABLE 2. Mean (*SD*) Maximum Isokinetic Strength (N) for Various Routines

Isokinetic Strength (N)	F_Y	F_Z
Sitting lateral pull down	104.75 (21.44)	599.48 (75.84)
Sitting military press	168.49 (51.73)	531.29 (122.3)
Open hatch	104.26 (24.77)	432.45 (73.88)
Sitting pull	353.85 (62.89)	97.86 (23.62)
Sitting push	343.49 (64.23)	281.70 (69.79)
Standing curl	107.24 (22.68)	445.31 (63.78)
Triceps press	78.82 (28.11)	355.01 (92.34)

Notes. F_Y—strength along the *Y* axis, i.e., along the sagittal and horizontal transverse plane, F_Z—strength along the *Z* axis, i.e., along the sagittal plane.

3.2. Pull Strength at Different Speeds

The average pull strength at 0.026 m/s over 400 s (14 repetitions) was 236.65 ± 39.14 N (Figure 5). The average pull strength at 0.130 m/s (43 repetitions) was 291.80 ± 65.83 N, while at 0.260 m/s (53 repetitions) it was 276.67 ± 87.18 N. At 0.026 m/s the average pull strength decreased 257.06–216.89 N over 14 repetitions (Figure 6). The decrease was linear ($p < .01$, $df = 104$). The decrease in strength per cycle was 4.94 N, while the overall strength decreased by 15.6% (the slope of linear regression line was –0.0257) (Figure 7). The average pull strength at 0.130 m/s decreased 288.65–266.84 N over 43 repetitions. The decrease in strength followed

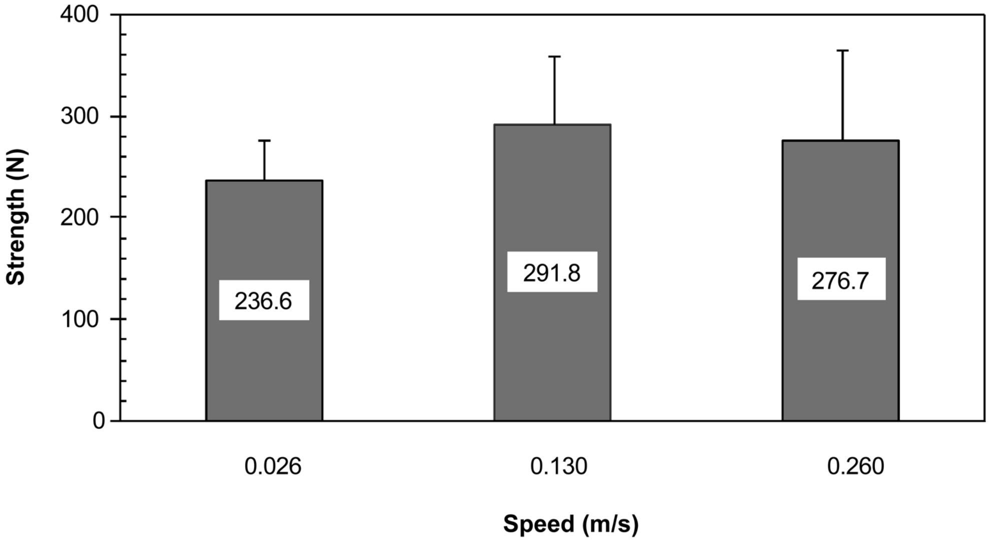

Figure 5. Average pull strength (N) over 400 s at 0.026, 0.130, and 0.260 m/s.

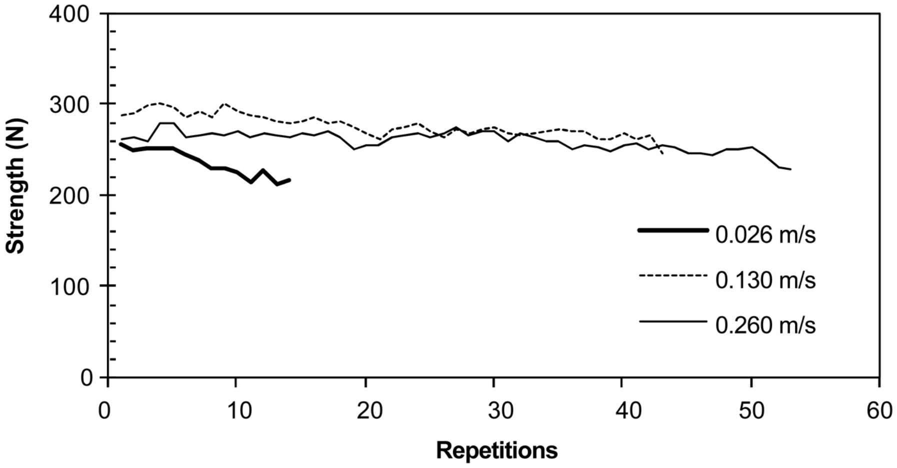

Figure 6. Variation in pull strength over 400 s at 0.026, 0.130, and 0.260 m/s.

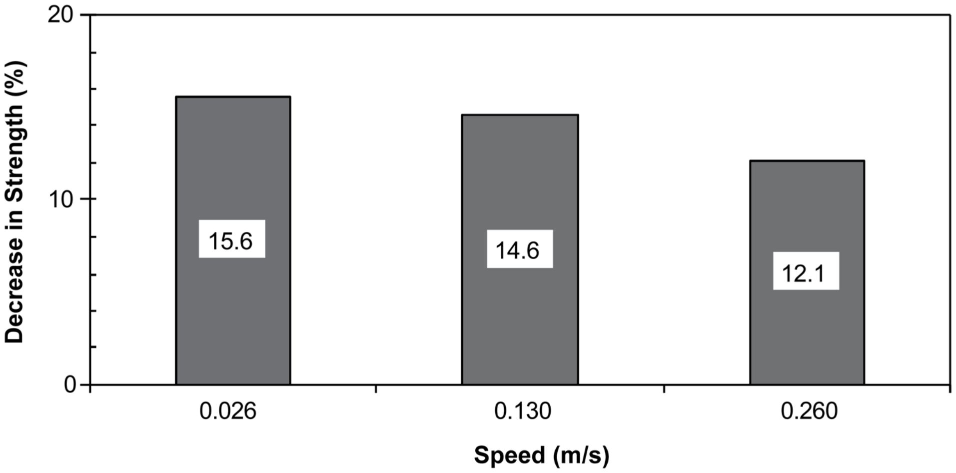

Figure 7. Decrease in pull strength (%) over 400 s at 0.026, 0.130, and 0.260 m/s.

a linear trend ($p < .01$, $df = 378$).The decrease in strength per cycle was 1.38 N, while overall strength decreased by 14.6% (the slope of linear regression line was –0.0209). At 0.260 m/s, the average pull strength decreased 273.87–245.76 N over 53 repetitions, i.e., 0.71 N per cycle. The decrease in strength followed a linear trend ($p < .01$, $df = 468$) and overall strength decreased by 12.1% (the slope of linear regression line was –0.0142).

The average isokinetic strength data at different speeds was fitted with the Gaussian function, $R^2 = .9$ (Figure 9). The equation of the curve was

$$y = 65.6 \times e^{(-((x-5.0)/7.603)^2)}.$$

The fitted curve was bell-shaped, indicating that the average strength increased with the initial increase in the speed reaching a speed at which the highest average isokinetic strength could be achieved. A further increase in speed resulted in a decrease in average isokinetic strength.

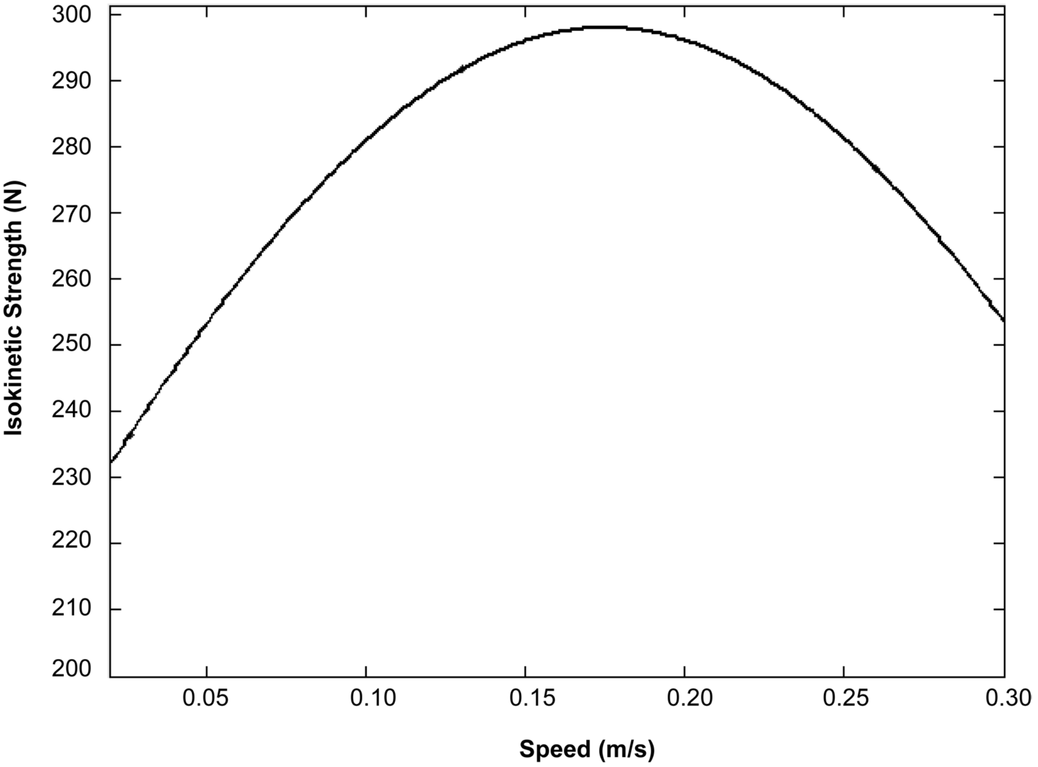

Figure 8. Gaussian curve fitted to average isokinetic strength data at different speeds.

4. DISCUSSION

An MMID at the anthropometry and biomechanics facility of NASA's Johnson Space Center was used to study various isokinetic upper-body exertions. This versatile device was used to understand the effect of different speeds of exertions on isokinetic strength. The custom-designed graphic user interface of the MMID made it possible to precisely control the speed at which the exercise or the task were performed. Among the seven upper-body exertions, the highest isokinetic strength along the sagittal and horizontal transverse plane was observed during sitting pull exertion, while along the sagittal plane the highest strength was recorded during the sitting lateral pull exertion.

The speed of exertion affected isokinetic strength. At a lower speed of 0.026 m/s the average sitting pull strength was lowest among the strengths measured at all three speeds. An increase in speed to 0.130 m/s increased the average sitting pull strength, while a further increase to 0.260 m/s reduced the average pull strength. In Garg and Beller's study, isokinetic strength was found to decrease with an increase in speed [14]. However, their participants performed lifting tasks at 0.41, 0.51, and 0.60 m/s. Shklar and Dvir studied isokinetic strength during shoulder flexion–extension, abduction–adduction, and internal and external rotation at 60, 120 and 180°/s [15]. Their results also showed that at progressively higher speeds, strength decreased during all the studied exertions. Garg and Beller's [14] and Shklar and Dvir's [15] speeds were comparatively much higher than the speeds used in this study. In the present study, even though for the initial increase in speed from 0.026 to 0.130 m/s, isokinetic strength increased, a decrease in strength was observed for the further increase from 0.130 to 0.260 m/s. Moreover, the Gaussian curve fitted to the average isokinetic strength and speed data (Figure 8) clearly predicts a decrease in strength at progressively higher speeds (>0.178 m/s).

Strength has been found to be dependent on various factors, e.g., type of muscle fiber, size of the muscle, length and speed of muscle at contraction, training, age, and gender [16]. An alteration in any of these factors could impact strength. The results of this study show that the relationship between isokinetic strength and speed followed a bell-shaped curve (Figure 8). The exertions performed too slowly or too fast result in submaximal average strengths. The highest average strength was observed at a rather medium speed. This medium speed could be called the optimum speed. At this speed not only could the highest strength be achieved but also the decrease in strength over time was comparatively minimum. At all three speeds in this study, the average isokinetic strength decreased linearly over the period of 400 s. The decrease was highest (15.6%) at 0.026 m/s, followed by 0.130 m/s (14.6%) and 0.260 m/s (12.1%). Although the percentage decrease in strength was lowest at 0.260 m/s, the average strength was also lower than that at 0.130 m/s.

The concept of optimum speed could be highly significant when designing the work pace of various MMH tasks. In the actual work setting, for the workers involved in repetitive MMH tasks, the weight of the object remains constant. If objects are lifted at relatively slow speed, workers could get tired early, as their strength decreases faster and also they are not be able to exert their maximal strength. On the other hand, carrying out the same task at a faster speed can also tire them early as they are not be able to exert their true maximal strength. In either case, workers tire quickly and are susceptible to injuries. However, if tasks are performed at an optimum speed, then workers can apply their maximal strength for a long period. This can reduce fatigue and help prevent injuries caused by overexertion.

We acknowledge that this study has a few limitations. First, the effect of speed on the strength was studied using a relative simple sitting pull type of exertion. Though the studied exertions provide a good understanding of the relationship between the speed and dynamic (isokinetic) strength, this exertion rarely resembles with the forceful exertions common at workplaces. Second, for standardization purposes, each participant performed the sitting pull exertion at different speeds using their maximum strength. In actual work conditions most of the time workers perform exertions by lifting, pushing, or pulling weights of different sizes and dimensions regardless of body size or strength. Future studies could be performed simulating actual occupational tasks involving forceful exertions to further improve our understanding of the speed–dynamic strength relationship.

In summary, a sophisticated cable-driven electromechanical MMID was used in this study to determine various upper-body isokinetic strengths. The effect of different speeds of exertions on the isokinetic strength was determined. The results of this study indicate that the tasks or the exertions that are performed at or near maximal must be performed at a medium (optimum) speed, rather than too fast or too slowly. For the sitting pull type of tasks, the optimum speed was found to be ~0.130 m/s. In industrial settings the concept of an optimum speed of performing the dynamic tasks could be used to decide on the work pace of various MMH tasks that require maximal or near maximal exertions.

REFERENCES

1. Aghazadeh F, Waly SM, Nason J. Static and dynamic strengths of males and females in seating and standing postures. In: Das B, Karwowski W, editors. Advances in occupational ergonomics and safety 1997. Amsterdam, The Netherlands: IOS Press;1997. p. 293–6.
2. Chaffin DB, Andersson GBJ. Occupational biomechanics. New York, NY, USA: Wiley-Interscience; 1999.
3. Hettinger T. Physiology of strength. Springfield, IL, USA: Thomas; 1961.
4. Mital A, Das B. Human strengths and occupational safety. Clin Biomech. 1987; 2:97–106.
5. Roebuck JA, Kroemer KHE, Thomson WG. Engineering anthropometry methods. New York, NY, USA: Wiley; 1975.
6. Carlson BR. Level of maxinum isometric strength and relative load isometric endurance. Ergonomics. 1969;12(3):429–35.
7. Heyward VH. Influence of static strength and intramuscular occlusion on submaximal static muscle endurance. Res Q. 1975;46(4):393–402.
8. Martens R, Sharkey BJ. Relationship of phasic and static strength and endurance. Res Q. 1966;37(3):435–7.
9. Noble L, McCraw LW. Comparative effects of isometric and isotonic traning programs on relative-load endurance and work capacity. Res Q. 1973;44(1):96–108.
10. Start KB Graham JS. Relationship between the relative and absolute isometric endurance of an isolated muscle group. Res Q. 1964;35:193–204.
11. Caldwell LS. Measurement of static muscle endurance. J Eng Psychol. 1964;3(1):16–22.
12. Garg A, Hegmann KT, Schwoerer BJ, Kapellusch JM. The effect of maximum voluntary contraction on endurance times for the shoulder girdle. Int J Ind Ergon. 2002;30(2):103–13.
13. Mital A, Channaveeraiah C, Fard HF, Khaledi H. Reliability of repetitive dynamic strengths as a screening tool for manual lifting tasks. Clin Biomech. 1986; 1(3):125–9.
14. Garg A, Beller D. A comparison of isokinetic lifting strength with static strength and maximum acceptable weight with special reference to speed of lifting. Ergonomics. 1994;37(8):1363–74.
15. Shklar A, Dvir Z. Isokinetic strength relationships in shoulder muscles. Clin Biomech. 1995;10(7):369–73.
16. Gaines JM, Talbot LA. Isokinetic strength testing in research and practice. Biol Res Nurs. 1999;1(1):57–64.