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Optimization of human-powered elastic mechanisms for endurance amplification

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Abstract Throughout the human body hundreds of muscles exert forces to stiffen and move the limbs and torso. During heavy exercise, only a small portion of these muscles fatigue. We report here a new kind of human-powered mechanism which amplifies endurance by altering the distribution of work output between fatiguing and nonfatiguing muscles. During heavy exercise, springs within the mechanism are stretched by muscles which would not fatigue if the exercise were conducted without the mechanism. This stored energy is then used to assist those muscles which typically would fatigue, resulting in an increase in endurance. A mathematical model is used to predict the efficiency with which the body can perform mechanical work at various spring stiffnesses for a particular heavy-exercise activity and mechanism. The model results support the hypothesis that the spring stiffnesses which maximize endurance also maximize the efficiency with which the human body can perform work.

1 Introduction

To test whether it is indeed possible for a human-powered mechanism to amplify endurance by using springs, a simple experiment was conducted on six human subjects. A spring was connected from each wrist to a waist harness (Fig. 1a). With this mechanism, each subject performed a cyclic activity described in Fig. 1 until complete exhaustion, repeating the experiment several times using different spring stiffnesses. The mean number of cycles to exhaustion, or the endurance, $\overline{N}$, normalize by $\overline{N}_o$, the mean value at zero stiffness, is plotted in Fig. 1b versus the dimensionless arm spring stiffness, K, defined as the measured stiffness of the added spring, k, multiplied by the maximum distance the spring was stretched, X_m, and divided by the subject's weight, W,

$$K = \frac{(kX_m)}{W} . \qquad (1)$$

Two experimental results are noted. Firstly, the endurance increases to a maximum value around $K \sim 0.25$ for each subject, and then rapidly decreases. Secondly, the fractional increase in endurance increases to approximately 1.5 to 2.5 times the endurance at zero added arm stiffness.

Figure 1a shows that to spring-load both arms, a mechanism was constructed comprising two latex rubber springs connecting each wrist to a waist harness. The springs were in equilibrium when both elbows were fully flexed with the wrists positioned at chest height. With this mechanism, a

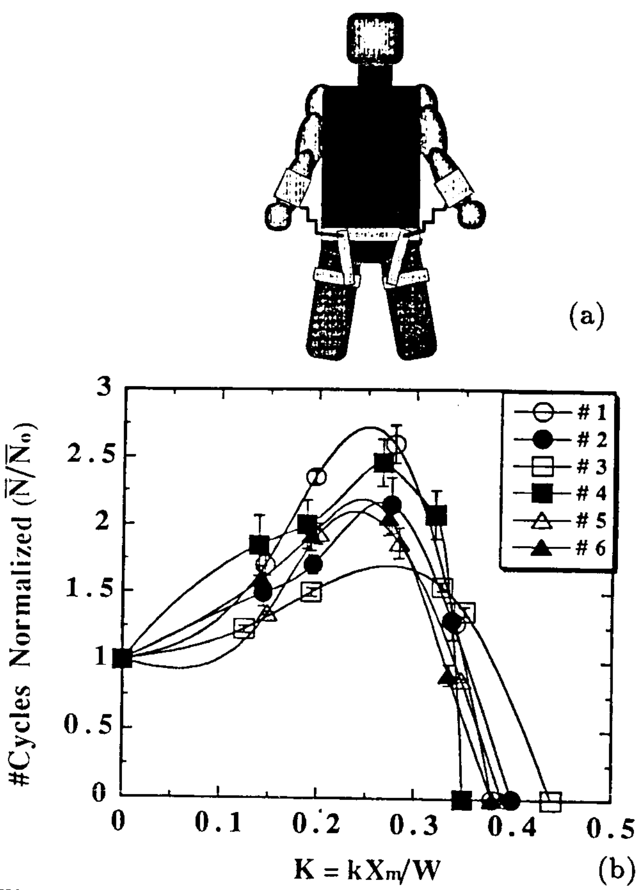

Fig. 1. (a) Experimental setup and (b) number of cycles to exhaustion in dependence on the spring stiffness

subject performed the following cyclic activity until complete exhaustion using a given spring stiffness. From a sitting position, a subject fully extended his arms to grasp a pull-up bar directly overhead, streching the arm springs. With the assistance of the stretched springs, the subject lifted his body upwards with his arms until his chin cleared the bar. Then the subject stood on the seat of a chair, released the bar, and sat down on the chair. Note that the cycle did not include lowering the body with the arms after pulling up. Energy was stored in the springs by extending the arms upward. Subjects were six males between the ages 19 and 29, all in good health but not specifically trained for this pull-up exercise. The experimental protocol was approved by the Committee on Use of Human Subjects at Harvard University. Each subject performed the experiment five times with a given spring stiffness using a total of five different spring stiffnesses. The order in which spring stiffnesses were used was randomized to rule out any sequential effects. In addition, each subject was required to use the same time to sit down after pulling up so that the time in which the arms were not being used during each cycle did not change. Between experiments, a subject was given two to three days of rest.

For six subjects in Fig. 1b, the mean number of cycles to exhaustion, $\overline{N}$, normalized by $\overline{N}_o$, the mean value at zero stiffness, is plotted versus the dimensionless arm spring stiffness, K. For each subject, a cubic spline curve passes through the mean of the normalized cycle values ($\pm$SE) at each of the five stiffness values. Arm spring stiffnesses, k, were measured by elongating the latex springs to various lengths and measuring the force in series with the spring using transducer (Kistler model 9203). For each spring, a linear model approximated the force versus elongation data well ($0.9 < r < 1.0$).

We hypothesize that the endurance changes are a consequence of changes in the efficiency with which the body can perform the required work for each cycle. We tested this hypothesis with a mathematical model describing the human body and spring mechanism to predict the optimal spring stiffness where endurance is maximized. The capacity of the extending arm to generate force during the first half of the cycle when the spring is elongating was modelled using a single effective extensor muscle. Similarly, the capacity of the flexing arm to generate force during the second half of the cycle when the body is being lifted upwards was modelled using an effective flexor muscle.

The efficiency, $\mathcal{E}$, as used here is defined as the muscle work to extend and flex one arm during each cycle, W_{arm}, divided by the metabolic cost to perform the work, E_{met}:

$$\mathcal{E} = \frac{W_{arm}}{E_{met}} . \tag{2}$$

The muscle work is equal to $WX_m/2$, since half the subject's weight is lifted a distance X_m by each arm during each cycle. A distribution-moment model of skeletal muscle[1] was used to compute a dimensionless metabolic rate, Ω, for constant velocity muscle contractions. The parameter Ω is defined as the metabolic rate, $\dot{E}$, divided by the product of the isometric muscle force, F_o, and the maximum contraction velocity, V_m (Fig. 2a),

$$\Omega = \frac{\dot{E}}{(F_o V_m)} . \tag{3}$$

With experimental measurements of X_m, F_o and V_m, the metabolic energy liberated per cycle, E_{met}, can be expressed in terms of muscle shortening velocity, V:

$$E_{met} = \int_o^{X_m} \left\{ F_o \left(\frac{V_m}{V} \right) \Omega \right\}_{ext} dX + \int_o^{X_m} \left\{ Fo \left(\frac{V_m}{V} \right) \Omega \right\}_{flex} dX , \tag{4}$$

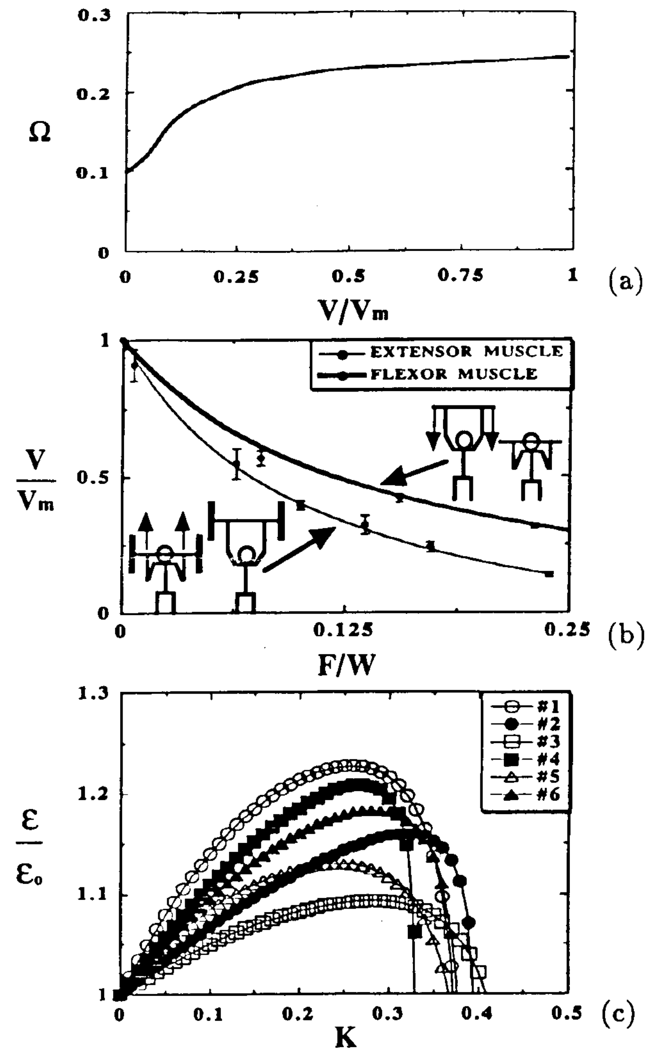

Fig. 2. Experimental results: (a) metabolic rate, (b) normalized arm velocity and (c) normalized efficiency

where the integration variable, X, is defined as the distance the arm spring is stretched. The first and second terms on the right of (4) are equal to the metabolic energy consumed during the extension and flexion periods, respectively. In each term, the metabolic energy rate, $(F_o V_m)\Omega$, is multiplied by dX/V, the time it takes an effective muscle to contract a distance dX at a shortening velocity V. To find the spring stiffness which maximizes the efficiency, the metabolic energy liberated per cycle, E_{met}, of (4) must be expressed in terms of dimensionless arm spring stiffness, K. To do this, we had to (1) experimentally determine the relationship between arm velocity and arm force during extension and flexion to define the force-velocity characteristics of the model's effective muscles, and (2) derive relationships between the effective muscle forces and the dimensionless arm spring stiffness.

The force-velocity properties of the arm during extension and flexion were measured for each subject (Fig. 2b). The relationship between arm velocity (V), and arm force (F) was found to be hyperbolic for both the extending and flexing arm, a known property of isolated skeletal muscle[2]. So

$$\frac{V}{V_m} = \frac{(M_1 - F/W)}{[M_2\,(F/W) + M_1]}\,, \tag{5}$$

where M_1 and M_2 are constants determined by fitting equation (5) to the force-velocity data.

Next, relationships between effective muscle forces and dimensionless arm spring stiffness must be derived. During the first half of the cycle when the subject extends both arms upward, stretching the springs, the force ratio exerted by an extending arm, F_e/W, is

$$\frac{F_e}{W} = K\left(\frac{X}{X_m}\right)\,. \tag{6}$$

During the second half of the cycle when the subject flexes both arms to lift the body, the force ratio exerted by a flexing arm, Ff/W, is equal to one half (the subject's weight) minus the spring force defined in (6),

$$\frac{F_f}{W} = \frac{1}{2} - K\left(\frac{X}{X_m}\right)\,. \tag{7}$$

By measuring the maximum acceleration of the body during the second half of the cycle when the body was lifted upward, inertial forces borne by each arm were determined to be less than three percent of the gravitational and elastic forces. Thus, inertial forces were ignored when writing (7). We also assumed that the arm springs obeyed Hooke's law, an assumption supported by experimental measurements of arm spring stiffnesses (Fig. 1).

Combining (2)-(7), the efficiency, $\mathcal{E}$, of equation (2) can be computed for a given K. In Fig. 2c, the efficiency curves for the six subjects, normalized by $\mathcal{E}_o$, the efficiency at zero stiffness, are plotted versus dimensionless arm spring stiffness, K. The efficiency maximums follow the same ordering of fractional increases from zero stiffness as the endurance curves of Fig. 1b (subject 3 has the smallest fractional increase, subjects 1 and 4 the largest, etc.). Furthermore, for each subject, the efficiency is maximized at a K close to the one that maximized the subject's endurance (Fig. 1b).

In Fig. 2a the dimensionless metabolic rate, Ω, for constant velocity muscle contractions is plotted versus the dimensionless contraction velocity, V/V_m. Analysis based on short-time steady-state behaviour seemed adequate for the purposes here because (1) the time in which the extensors and flexors were active per cycle was small (< 3 sec), and (2) both V_m and F_o changed little (< 5%) with changes in elbow flexion. The metabolic rate employed here uses parameters corresponding to mean characteristics for slow and fast muscle fiber types and thus may be appropriate for mixed-type human muscles. For example, the ratio of metabolic rate at maximum contraction velocity, Vm, to that at zero velocity is approximately 5 for the slow soleus and 1.5 for the fast EDL of mouse at 21°C[3]. The value used here is 2.5, approximately the mean of the slow and fast muscle values. In Fig. 2b representative force-velocity curves for the extending and flexing arm are plotted for one subject. The extensor data was collected by asking each subject to press a barbell directly overhead in a manner similar to the arm motion during the first half of the cycle when the springs were stretched. The velocity of extension was determined by measuring the position of the barbell at various times with a linear potentiometer designed specifically for the task, plotting vertical height versus time, and taking the slope of a linearly-fitted curve. The force, F, generated by the extending arms was determined by weighing the barbell. Inertial forces were ignored because the barbell velocity was nearly constant except at the very beginning and end of the motion. The flexor data was gathered using similar methods, except that instead of pressing a barbell upward, each subject pulled a lightweight bar downward in a manner similar to the arm motion during the second half of the cycle when the body was lifted upwards. Since a barbell weight was connected to the lightweight bar by a cable passing through a pulley, pulling the bar downwards lifted the weight upwards. The maximum velocities, V_m, were determined by flexing or extending the arms with no weight in hand. The isometric forces, F_o, were determined by adding weight to the barbell until the subject could just hold the weight statically with arms flexed. For the force-velocity curves of Fig. 2b, F/W at $V/V_m = 0$, or F_o/W, has a value of 0.39 for the effective extensor and 0.8 for the effective flexor. Experimental uncertainties were determined by repeating an experiment at a given weight five times and then computing the standard error. Figure 2c shows the normalized efficiency, $\mathcal{E}/\mathcal{E}_o$, which is plotted versus the dimensionless arm spring stiffness, K. For each subject, an efficiency curve was generated by numerically integrating equation (4) at particular stiffness values, computing the efficiency, $\mathcal{E}$, defined in (2), and normalizing each efficiency value to the efficiency at zero spring stiffness, $\mathcal{E}_o$.

There are many practical applications for the ideas presented in this study. For example, a crutch has been constructed with an elbow spring to maximize the edurance of physically disabled persons in climbing stairs. When the crutch user flexes both elbows to place the crutch tips on a stair tread, elbow springs compress and store energy. This stored energy helps the crutch user extend the arms in rising up the next step. If the elbow spring stiffness is tuned optimally using the analysis techniques outlined here, the crutch user's endurance for climbing stairways benefits significantly. We conclude that human-powered elastic mechanisms can amplify endurance by increasing the efficiency with which the body can perform mechanical work.

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