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Revisiting the positive aspects of negative work

Steven Elmer and Paul LaStayo discuss Abbott et al.'s classic paper 'The physiological cost of negative work', published in *The Journal of Physiology* in 1952.

Two bicycles and one chain: with these three components, Bernard 'Bud' Abbott, Brenda Bigland and Murdoch Ritchie constructed a unique cycle contraption (Abbott et al., 1952). The ergometer that they devised was used to compare the cost of performing muscle shortening contractions inducing 'positive work' with muscle lengthening contractions inducing 'negative work'. This experiment, over 60 years ago, is time-honored as it was the first to link human whole-body energetics with muscle force–velocity characteristics previously measured in isolated muscle. Moreover, this groundbreaking study sparked a series of subsequent experiments aimed at further understanding the unique physiological characteristics of lengthening contractions and inspired the use of negative work in rehabilitation and sport training arenas. In this Classics forum we briefly revisit how this unique experiment has led to current explorations of the 'positive aspects of negative work'.

For the experiment, Abbott's team connected the two bicycles back-to-back via a single chain. (Note: evidently this connection also served as a metaphor in that Brenda Bigland and Murdoch Ritchie eventually married.) One cyclist (Ritchie) pedaled forward while the other cyclist (Bigland) resisted the motion of the reverse moving pedals (Fig. 1). During the forward pedaling condition, leg muscles (e.g. quadriceps) produced force while shortening (i.e. concentric muscle contractions), whereas resisting the pedal action generated leg muscle forces while lengthening (i.e. eccentric muscle contractions). Thus, the two movements and magnitude of work were for the most part mirror opposites of one another, with the only differences being the mode of pedaling movement (pushing versus resisting), type of muscle contraction (shortening versus lengthening) and work induced (positive versus negative). The study demonstrated that the oxygen consumption of the 'resisting' cyclist was only a fraction (up to approximately one-fifth) of that of the forward cyclist. Indeed, as demonstrated by the authors themselves, Bigland, a young, petite woman, was able to resist and exhaust the forward pedaling efforts of Ritchie, a large, powerful man (Bigland-Ritchie, 1995). At the time, this investigation was not only well received by the scientific community, but also served as a source of physiologic entertainment. The ergometer was coined the 'push me, pull you' device after Dr Doolittle's two-headed animal and was demonstrated twice at the Royal Society and intrigued many, including the Lord Mayor of London (Bigland-Ritchie, 1995).

Prior to 1952, most investigations on muscle contraction involved isolated muscles performing isometric and/or shortening contractions. Indeed, Abbott and his co-authors emphasized, 'the absorption of work during forcible lengthening has been almost entirely neglected.' They also remind the reader that 'in the living animal active muscles are regularly stretched, and in the process mechanical work is absorbed in them.' Previous investigators (Fick, 1882; Katz, 1939) noted that muscle fibers produced greater force during active lengthening compared with active shortening. Another important observation was that less energy was liberated during active lengthening (Abbott et al., 1951; Fenn, 1924). With these unique differences in mind, Abbott's team set out to apply these previous findings specifically to human exercise, and Abbott et al.'s experimental finding has been verified repeatedly by subsequent investigators (Bigland-Ritchie and Woods, 1976; Dufour et al., 2007; Dufour et al., 2004; Elmer et al., 2013a; Elmer et al., 2013b; Henriksson et al., 1972; Perrey et al., 2001). In fact, the design of the 1952 experiment was suggested by A. V. Hill (Bigland-Ritchie, 1995), who was exploring muscle as a thermodynamic machine by correlating the mechanical events and heat production associated with contraction and recovery. Hill also recommended using the terms positive and negative work (Bigland-Ritchie, 1995). As described above, there was a large difference in oxygen consumption between positive and negative work. Because each fiber could exert a larger force during muscle lengthening than shortening, the authors interpreted the differences in oxygen consumption between positive and negative work to reflect differences in the total number of active muscle fibers. Later, using a similar experimental design, Bigland-Ritchie and Woods (Bigland-Ritchie and Woods, 1976) expanded upon this initial work by integrating measures of oxygen consumption along with surface electromyography of quadriceps muscles to approximate the oxygen uptake per active muscle fiber. These authors reported that reduced muscle activity during negative work confirmed that fewer muscle fibers were recruited and suggested that the recruited muscle fibers consumed less oxygen. Taken together, these initial findings by Abbott's team and others established that the energy cost to produce the same absolute work rate was clearly lower during negative work – though today's explanation for reduced energetic cost goes beyond the muscle recruitment level (Nishikawa et al., 2012). These findings from 1952 also offered for the first time a more systemic view on the understanding of muscular function during human exercise. This approach would later enable Bigland to make seminal contributions to the understanding of the processes underlying neuromuscular fatigue. Finally, these results clearly demonstrated that muscle lengthening was not simply the opposite of muscle shortening! In other words, the chemical reactions that consume ATP during shortening contractions were not simply reversed during lengthening contractions.

Classics is an occasional column, featuring historic publications from the literature. Written by modern experts in the field, these articles discuss each classic paper's impact on the field of biology and their own work.

Looking back at this paper, many physiologists can appreciate the fact that Abbott's team made every effort to connect their findings during human exercise to previous work involving isolated muscle (Thomas et al., 1995). However, the underlying mechanisms that give rise to the reduced cost of negative work are not well understood. A few authors have speculated that this phenomenon might occur because the actin–myosin bonds are disrupted mechanically rather than undergo an ATP-dependent detachment (Flitney and Hirst, 1978; Menard et al., 1991), as is the case during shortening contractions. Interestingly, Thomas McMahon referred to lengthening contractions as the 'dark side' of the force–velocity curve, a reference to the popular Star Wars Movie series. Nevertheless, the cost of negative work is considerably lower compared with positive work and the pattern of muscle activation is unique.

Nearly 50 years after this novel experiment, lengthening contractions and negative work made their way into rehabilitation and sport training settings. That is, the unique physiological characteristics of lengthening contractions highlighted by Abbott's team (i.e. high-force, low-cost) became suitable for enhancing muscle growth and function without injuring muscle. Indeed, we and other investigators have demonstrated that chronic training (e.g. 10–30 min, 2–3 times week^{-1}, 6–12 weeks) with resistance exercise via negative eccentrically induced work (RENEW) can serve as a potent stimulus for improving muscular function (e.g. quadriceps size, strength and mobility) in a variety of populations ranging from patients with central limitations to individuals with orthopedic injuries and impairments, and competitive athletes (for recent reviews, see Isner-Horobeti et al., 2013; LaStayo et al., 2014). Collectively, these examples highlight the novelty of RENEW training in that only relatively low levels of perceived exertion are required to generate high negative work rates that can induce positive changes in muscular function without producing profound levels of muscle damage. Conversely, traditional resistance training (involving a combination of shortening and lengthening contractions) that requires high levels of perceived exertion to produce modest work rates

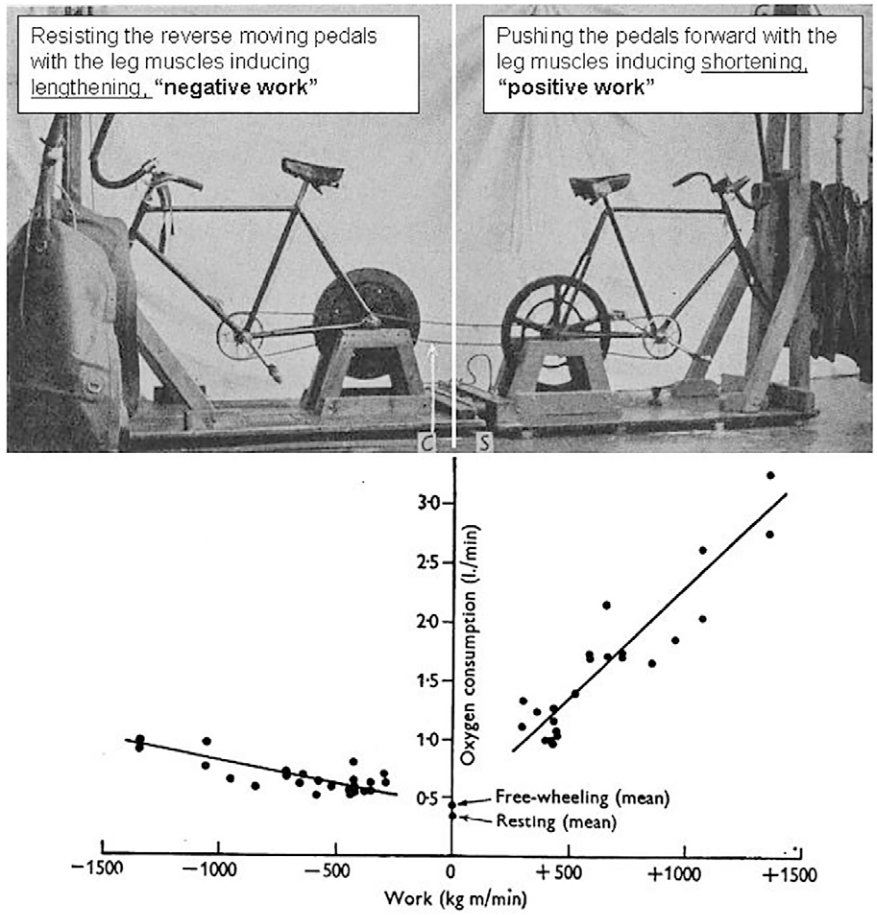

Fig. 1. Top panel: the experimental ergometer consisting of two bicycles positioned back to back and coupled with a single chain. During the forward pedaling condition (right), the participant's leg muscles (e.g. quadriceps) produced force while shortening ('positive work'), whereas resisting the pedal action (left), the muscles generated force while lengthening ('negative work'). Bottom panel: the original figure illustrating variations in oxygen consumption measured during positive and negative work. Note that absolute work rates were similar between the positive and negative conditions. Current figure was generated using figs 1 and 3 from the original paper (Abbott et al., 1952).

can often pose a barrier to exercise compliance and may (at times) not be sufficient to stimulate changes in muscular function. On a personal note, our motivation to utilize negative work with patient and athletic populations can be linked directly back to Abbott's investigation. More importantly, this application of negative work is considered a cutting-edge rehabilitation and training modality and has been reviewed in detail in sports medicine (Isner-Horobeti et al., 2013), rehabilitation (LaStayo et al., 2003) and applied physiology journals (LaStayo et al., 2014).

While the two bicycle–single chain, 'push me, pull you' ergometer was eventually replaced by commercially available concentric and eccentric cycle ergometers, the novel setup that facilitated this experiment is still remembered and revered. Specifically, the historic black-and-white photo of the experimental apparatus re-appeared in the literature in 1995 [fig. 1 in Bigland-Ritchie (Bigland-Ritchie, 1995)] and as recently as 2013 [fig. 1 in Isner-Horobeti et al. (Isner-Horobeti et al., 2013)]. Likewise, the story of Bigland quickly tiring out Ritchie has been passed on in the literature (Isner-Horobeti et al., 2013; Lindstedt et al., 2001), laboratory and classroom. Further, our group (Elmer et al., 2013a; Elmer et al., 2013b) recently re-visited this historic work by comparing the cost of positive and negative work during upper body arm cycle ergometry, and the results suggest that the unique physiological characteristics of lengthening contractions are consistent and, for the most part, generalizable across muscle groups. These examples remind us of the potential long-lasting 'positive impact' of 'negative work'. At this time, researchers, clinicians and athletes continue to utilize the concept of 'high-force, low-cost' in eccentrically biased rehabilitation and training programs.

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