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Effects of muscle fatigue on grip and load force coordination and performance of manipulation tasks

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HIGHLIGHTS

- Effects of muscle fatigue on various manipulation tasks were explored.
- The ability to control external loads remained unaffected by fatigue.
- Both the hand grip force and its coupling with external load were reduced.
- The findings explain why external objects are often dropped by fatigued muscles.

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ABSTRACT

Muscle fatigue is known to be associated with a deteriorated muscle coordination and impaired movement performance in variety of voluntary movements. The aim of this study was to investigate the generally underexplored effect of muscle fatigue on both the coordination between grip force (GF; the force component perpendicular to the hand–object contact area that provides friction) and load force (LF; the parallel force component that can move the object or support the body) as well as movement performance in manipulation tasks. Fifteen participants performed a variety of static and dynamic manipulations both with and without a preceding procedure designed to fatigue the arm and hand muscles. The tasks involved exertion of ramp-and-hold and oscillation patterns of LF against an externally fixed instrumented device, and a simple lift of a freely moving device. The results revealed a fatigue-associated decrease in GF scaling (i.e., the magnitude of GF relative to LF) and GF–LF coupling (correlation between GF and LF), while the task performance regarding the accuracy of exertion of the prescribed LF profiles remained unaffected. We conclude that muscle fatigue both partly decouples GF from LF and reduces the overall GF magnitude, which could potentially explain why hand-held objects are more likely to drop when manipulated with fatigued muscles. However, the unaffected task performance could be explained either by the relatively low level of muscle forces required by the tested tasks, the moderate level of the fatigue imposed, or both.

1. Introduction

The ability to manipulate objects represents a crucial motor function of daily living, while the hand per se is a frequently used model in the studies of biomechanics and motor control phenomena [12,15,23,27]. Among a number of different approaches, the force analysis of object manipulation has frequently been applied. This force analysis is typically based on a simple mechanical model of a vertically oriented handheld object (Fig. 1A). The interaction force is decomposed into the load force (LF) that originates from friction and acts in parallel to the contact surface to overcome the object's weight and inertia, while grip force (GF) is applied perpendicularly to the object to provide both the friction and enable the control of the object's position [7,13,15]. In general, GF needs to be scaled high enough to prevent slippage, but not excessively high to cause either object deformation or muscle fatigue.

Numerous studies, performed on a variety of static and free movement tasks, have consistently revealed a high level of GF–LF coordination through different aspects of GF control [7,13,15,27]. Among others, GF is typically scaled to provide a relatively low and stable GF–LF ratio [15], while continuous coupling of GF with ongoing LF changes has been observed through a high GF–LF correlation and a low GF–LF time lag [7,15,18,26], indicating the

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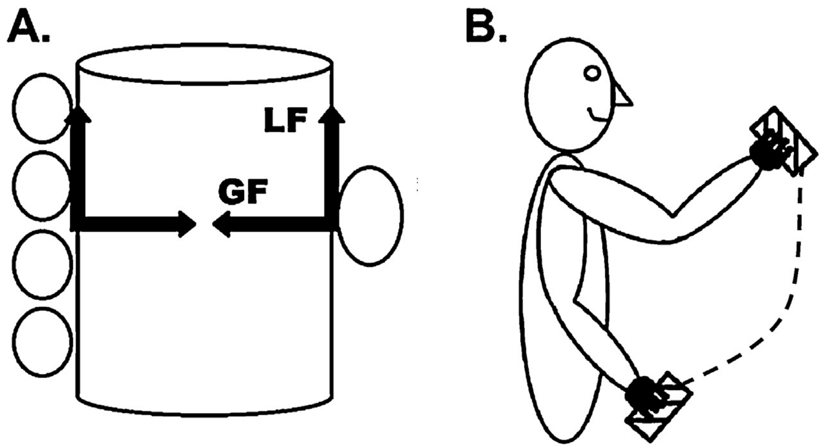

Fig. 1. (A) Simple model of object manipulation. The circles illustrate the tips of all five digits applying a precision grip to produce the contact force that can be decomposed into the normal (i.e., grip force; GF) and parallel component (load force; LF). (B) Illustration of the fatigue protocol. Participants oscillated the weighted object from the shoulder to hip level, and back.

involvement of "feed-forward" neural control mechanisms [15,16]. However, various factors can adversely affect GF–LF coordination, such as a frequent switching of LF direction [5,12], an increase in the task complexity [18,25,27], or the presence of neural diseases [10,19,22]. Of importance for the present study is the reduced GF–LF coordination, observed either in various tasks or in different patient populations, usually associated with impaired task performance [17,21]. Therefore, it has been concluded that the GF–LF coordination in manipulation tasks could not be only a 'window' into the neural mechanisms of muscle control and movement coordination [5,12,15,23], but also a basis for developing standard quantitative tests of hand function in various populations [17,19,21].

Muscle fatigue represents an exercise-induced reduction in the force-generating capacity of muscle, caused by changes within both the CNS and the acting muscles [6]. Fatigue typically decreases maximal voluntary activation of muscle [9], disrupts excitation–contraction coupling [1] and impairs both the movement coordination [2,8] and performance [3]. Regarding the effects on hand function, the muscle fatigue has been shown to reduce the applied GF [20,24], to increase the fluctuation of GF, and to decrease the coupling between GF and LF in simple lifting tasks [24]. The effects of fatigue on both the coordination of individual fingers producing GF and its adaptation have also been studied [4,23]. However, taking into account both the role that GF–LF coordination has played in the studies of hand function and its potential importance for future neurological testing, it is surprising that the effects of fatigue on GF–LF coordination have been largely neglected. Only recently a deteriorated GF–LF coordination in a simple lifting task performed with a pinch grip has been observed [24].

The purpose of the present study is to investigate the effects of muscle fatigue on the GF–LF coordination and performance in a variety of manipulation tasks. Based on the previously documented general effects of muscle fatigue on both task performance and movement coordination [1,2,8,9], as well as on the positive relationship between the GF–LF coordination and performance in manipulation tasks [11,13,21], it is hypothesized that the applied fatiguing procedure would result in both impaired GF–LF coordination and deteriorated manipulation performance.

2. Methods

Fifteen healthy right-handed participants were recruited (10 males and 5 females, 20–30 years of age). They were without neurological problems and recent injuries to upper limbs. The experiment was approved by the IRB of the University of Delaware and conducted in accordance with the Declaration of Helsinki.

A custom designed device, used in the previous studies of hand function [14,26], was utilized to record GF and LF produced by the participants (Fig. 1A). The instrumented handle used in this study consisted of two parallel grasping surfaces covered with high friction rubber and connected by a single axis force transducer (WMC-50, Interface Inc., USA). A multi-axis force transducer (Mini40, ATI, USA) was attached beneath each handle either to allow for attachment of the handle either to a fixed external support or to an added brass weight. The single-axis force transducer within the handle records the compression force exerted against the one side of the handle, while the multi-axis force transducer underneath the handle records all three components of the net force applied against the handle (see [14,26] for the details of GF and LF calculation). The externally fixed handle served for testing static manipulation tasks, while the other was attached to a 200 g mass (total weight 5 N) and could be freely manipulated, which was utilized for both determining maximum precision GF (i.e., the force exerted upon the handle by the tips of the fingers and the thumb) and performing a simple lift task.

Prior to testing, participants washed and dried their hands. The handles of the experimental device were washed with isopropyl alcohol to eliminate any residue from prior testing sessions. The participants stood facing a table that contained the device handles and a computer screen that provided visual feedback. Their maximum GF was assessed using the free-manipulation handle. Specifically, subjects were instructed to grasp the free handle with a precision grip (i.e., the tips of all 5 digits involved; see Fig. 1) with their upper arm positioned vertically and elbow flexed 90°. With the use of verbal encouragement from the experimenter and the instruction to "squeeze as hard as possible," the participants were given 4 s to record their maximum precision grip. This measure was taken both before and after the fatiguing protocol.

Three tasks were tested using the same grip as in testing the maximum GF. *Ramp-and-hold* task required the participants to trace the line shown on the computer monitor by pulling up on the externally fixed handle to produce a tension force [14,17]. The line remained constant at 0 N for 2 s, increased thereafter gradually from 0 N to 10 N at a constant rate for 4 s, and finally remained constant at 10 N for final 4 s. *Oscillation task* required the participant to produce an oscillating force within the range from 2 N to 10 N of tension for 12 s at a frequency of 1.5 Hz paced by a metronome [11,14,17]. This frequency was chosen because it should be in the middle of the frequency range that allows for the comfortable execution of this type