June 1, 2006

Digit force control in older adults: Benefits of resistance-training?

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DIGIT FORCE CONTROL IN OLDER ADULTS: BENEFITS OF RESISTANCE-TRAINING?

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Abstract

This paper seeks to review the effect on digit force control of: 1) the ageing process; and 2) the resistance-training in older adults. Significant age-related decreases in finger-pinch force control were observed in many but not all studies. Those that didn't report age-related differences involved bi-digit finger-pinch tasks requiring the production of constant forces only. This suggests that the age-related decline in force control becomes more pronounced the more challenging the force production task. While three studies reported that resistance-training improved older adults' digit force control capabilities, it is unclear if these improvements would occur in tasks that: 1) require the coordinated activity of multiple fingers and muscles; but 2) are not specifically performed during training. Future research in this area should use more "real-world" tasks to increase the generalisability of these findings, while recording individual digit forces and muscle activity to gain further insight into the mechanisms responsible.

Introduction

This paper seeks to review the effect of the ageing process on digit force control and the potential benefits that resistance-training may have in improving such function in older adults. Particular emphasis will be placed on force control in the context of the finger-pinch, as the finger-pinch is a fundamental grasping style that is commonly used in many upper limb activities of daily living, especially those requiring high levels of precision and dexterity (Shumway-Cook & Woollacott, 2001).

Importance of digit force control

One of the main factors that separate humans from all other animals is our highly developed ability to manipulate the environment with the hand and fingers (Jones, 1996; Schieber & Santello, 2004; Vallbo & Wessberg, 1996). In particular, the unique anatomical features of the human hand and fingers allow the dexterous manipulation of hand-held objects during a range of activities of daily living. This high level of dexterity can be easily observed during the performance of such diverse tasks as eating, drinking, typing, writing, sewing and dressing.

In order to perform these activities of daily living, the object must first be securely grasped. This requires the performer to predict the necessary grip force based on the apparent dimensions, density and surface conditions of the object (Baud-Bovy & Soechting, 2002; Flanagan, Burstedt, & Johansson, 1999; Flanagan & Tresilian, 1994). The ratio of the grip to load force determines the stability of the grasp and the relative dexterity of manipulation (Baud-Bovy & Soechting, 2002; Cole & Johansson, 1993). If the grip:load force ratio becomes less than the slip force (inverse of the coefficient of friction), the object will be dropped (Baud-Bovy & Soechting, 2002; Cole, 1991). On the other hand, excessive grip:load force ratios (also called safety margins) will result in increased energy expenditure, earlier onset of muscle fatigue and a reduction in dexterity and precision of movement (Cole, 1991; Flanagan & Wing, 1993). Even assuming that during the initial grasp of the object, the grip:load and slip force ratios are within the normal range, small oscillations in the grip force are continually occurring. These oscillations will alter the grip:load and/or slip force ratios, thereby potentially increasing the risk of slippage or reducing the ability to dexterously manipulate the object. Digit force oscillations will also cause time-varying changes in the linear and/or angular accelerations of the hand, so that the hand and object are displaced in linear and angular directions from their intended position.

It is therefore apparent that if an individual is unable for whatever reason to coordinate and control the force outputs of the involved digits, a loss of grasping performance, independence and quality of life will occur (Carmeli, Patish, & Coleman, 2003; Hughes et al., 1997). Such a loss of grasping performance has been shown to occur in older adults (Contreras-Vidal, Teulings, & Stelmach, 1998; Hackel, Wolfe, Bang, & Canfield, 1992; Laursen, Jensen, & Ratkevicius, 2001; Ranganathan, Siemionow, Saghal, & Yue, 2001; Spirduso, 1995) and in patients suffering from neurological conditions (Rearick, Stelmach, Leis, & Santello, 2002; Vaillancourt, Slifkin, & Newell, 2001b). It could therefore be hypothesised that training-related improvements in digit force control may enhance the grasping performance and quality of life of these populations.

Methods used to quantify force control

A number of methods have been used to quantify digit force control in the literature. The most common of these measures appear to be force steadiness (force variability) and targeting error. Force variability can be defined as the steadiness of the force output and has been expressed in both absolute and relative terms. Absolute force variability is calculated as the standard deviation of the force output and is measured in the units of force, Newtons (N) (Bilodeau, Keen, Sweeney, Shields, & Enoka, 2000; Cole, 1991; Galganski, Fuglevand, & Enoka, 1993). Relative force variability is the coefficient of variation of force output, and is therefore a percentage (Christou, Jakobi, Critchlow, Fleshner, & Enoka, 2004; Hamilton, Jones, & Wolpert, 2004; Laidlaw, Bilodeau, & Enoka, 2000). Targeting error is generally defined as the root mean square (RMS) difference between the actual force output produced by the performer and the target force and is normally expressed in absolute terms, i.e. N (Blank, Heizer, & von Vob, 1999; Lazarus & Haynes, 1997; Shim, Lay, Zatsiorsky, & Latash, 2004; Vaillancourt, Slifkin, & Newell, 2002). Two studies has also normalised targeting error to the maximum voluntary contraction (MVC) force, thereby expressing it as a relative (percentage) error (Keogh, Morrison, & Barrett, 2006; Loscher & Gallasch, 1993).

Factors influencing force control

While the precise control of digit forces appears to be dependent on many factors, much of the literature has examined the role of the motor unit (Enoka, 1997b; Erim, Beg, Burke, & De Luca, 1999; Laidlaw et al., 2000; Vaillancourt, Larsson, & Newell, 2003). Net force output is directly controlled (graded) by the size and firing rate of the active MU in the agonist, synergist and antagonist muscles (Enoka, 1997b). As the most recently recruited MU has not reached tetanus, the variability in its firing rate will directly contribute to the variability in the total force output and the decline in force control (Enoka, 1997b; Laidlaw et al., 2000). The loss of force control may also become more pronounced with increased average MU size (force) (Galganski et al., 1993; Keen, Yue, & Enoka, 1994), modulation of MU firing rate (Enoka et al., 2003; Semmler, Kornatz, & Enoka, 2003) and alterations in the synchrony between MU recruitment and MU firing rate (Erim et al., 1999).

Sensorimotor processes also appear to play an important role in the control of digit forces. The majority (> 90%) of power in the force frequency spectrum has been found below 4 Hz (Christou et al., 2004; Deutsch & Newell, 2004; Erim et al., 1999; Keogh et al., 2006; Morrison & Newell, 1998; Slifkin & Newell, 2000; Vaillancourt & Newell, 2003). It has been suggested that the dominance of low frequency power reflects the sensorimotor processes utilised during such tasks (Christou et al., 2004; Freund & Hefter, 1993; Slifkin, Vaillancourt, & Newell, 2000; Vaillancourt & Newell, 2003; Vaillancourt, Slifkin, & Newell, 2001a). Such results would indicate that accurate and timely sensory information is also required for optimal force control. In particular, tactile sensitivity (Cole, 1991; Kinoshita & Francis, 1996) and vision (Slifkin et al., 2000; Vaillancourt et al., 2001a; Vaillancourt, Slifkin, & Newell, 2001c) appear to be two of the more important forms of sensory information required to maximise the control of digit forces.

When multiple digits are used to produce a resultant force, the pattern of coupling (coordination) between the digits and/or muscles may also influence the ultimate level of force control. For example, there is some evidence to suggest that the optimal control of multi-digit force is obtained when the digits are coupled in a compensatory manner (Latash, Gelfand, Li, & Zatsiorsky, 1998; Latash, Scholz, Danion, & Schoner, 2001, 2002; Santello & Soechting, 2000; Scholz, Danion, Latash, & Schoner, 2002; Shinohara, Li, Kang, Zatsiorsky, & Latash, 2003; Shinohara, Scholz, Zatsiorsky, & Latash, 2004). This compensatory coupling (also referred to as force co-variation by Latash and colleagues) allows some of the variability in the force output of one digit to be compensated for by an opposite change in the force output of the remaining digit(s). Such coupling allows the variability of the total (resultant) force to be substantially less than the sum of the each of the individual digits' force variability. As most of these studies have used finger depression (pressing) tasks to assess inter-digit force coordination, the role of these synergies in multi-finger finger-pinch tasks is less clear. This is especially evident with respect to the role that changes in inter-digit coordination may play in explaining the age- and training-related changes in force control.

Age-related changes in neuromuscular function

Older adults typically experience a loss of muscle capacity. For example, they have reduced aerobic power (Harridge, Magnusson, & Saltin, 1997; Wiebe, Gledhill, Jamnik, & Ferguson, 1999), muscular strength and endurance (Harridge et al., 1997; Hurley, Ree, & Newham, 1998; Imrhan & Loo, 1989) and rate of force development (Harridge et al., 1997; Thelen, Schultz, Alexander, & Ashton-Miller, 1996) compared to young adults. Although these reductions in muscle capacity may be multi-factorial in origin (Barry & Carson, 2004; Enoka et al., 2003), they all typically result in diminished functional status (muscle function).

A loss of muscle function can be readily observed in both lower- and upper-body dominated activities of daily living for older adults. They may suffer a loss of postural stability and have a reduced velocity when walking and getting up from a chair (sit to stand) than young adults (Brown, Sinacore, & Host, 1995; McKenzie & Brown, 2004; Sakari-Rantala, Era, Rantanen, & Heikkinen, 1998; Winter, 1991; Wu, 1998). Older adults are also typically slower and less accurate when performing upper limb tasks such as writing, lifting, holding and manipulating hand-held objects (Contreras-Vidal et al., 1998; Francis & Spirduso, 2000; Hackel et al., 1992; Laursen et al., 2001; Ranganathan, Siemionow, Saghal et al., 2001; Warabi, Noda, & Kato, 1986).

Older adults' loss of grasping ability, mediated at least in part by their relative inability to control their digit forces is widely believed to reflect age-related declines in neuromuscular function, particularly in MU control and sensorimotor processing. For example, the decreased force control of older adults could reflect their increased average MU force (Galganski et al., 1993; Keen et al., 1994), MU firing rate variability (Laidlaw et al., 2000) and modulation of MU firing rate (Enoka et al., 2003; Semmler et al., 2003), altered synchrony between MU recruitment and MU firing rate (Erim et al., 1999) or reduced tactile sensitivity (Cole, 1991; Kinoshita & Francis, 1996). Another factor that may theoretically contribute to a relative loss of finger-pinch force control in older adults is the pattern of coupling (coordination) between the digits and/or muscles (Santello & Soechting, 2000; Schieber & Santello, 2004). However, as only three published papers have examined the effect of ageing on finger-pinch force control and inter-digit coordination (Keogh et al., 2006; Shim et al., 2004; Vaillancourt et al., 2002), it is somewhat unclear as to whether this factor contributes to those changes seen in the control of finger-pinch force in older subjects.

Age-related changes in force control

Due to the general decline in neuromuscular and possibly coordinative function seen as a function of the ageing process, it would be expected that older adults would have significantly less force control than young adults. However, the literature is actually somewhat equivocal for the effect of ageing on finger-pinch force control. This is highlighted in Table 1, where older adults have been found to have significantly reduced force control than young adults in some (Christou et al., 2004; Cole, 1991; Keogh et al., 2006; Kinoshita & Francis, 1996; Lazarus & Haynes, 1997; Ranganathan, Siemionow, Saghal et al., 2001; Shim et al., 2004) but not all studies (Cole & Beck, 1994; Cole, Rotella, & Harper, 1999; Vaillancourt et al., 2001b, 2002).

INSERT TABLE 1 about here

The relative equivalence of these results could reflect many factors, including inter-study variation in the availability and gain of visual feedback, the loads used (absolute vs relative; low vs moderate vs high) and the manner in which force control was quantified (force variability vs targeting error; absolute vs relative). However, it is argued that the main factor(s) underlying this inconsistency is the number of digits utilised in the finger-pinch tasks and perhaps the shape of the target force (constant vs sinusoidal or ramp).

All of the studies that used multi-finger finger-pinch tasks and/or involved the production of non-constant forces (Keogh et al., 2006; Lazarus & Haynes, 1997; Shim et al., 2004) found significantly reduced force control in older than young adults. In contrast, the four studies that found no significant age-related differences in finger-pinch force control all utilised finger-pinch tasks involving just the thumb and index finger and the production of constant forces. Such results appear indicative of a trend where the age-related loss of finger-pinch force control becomes more pronounced as the number of digits and/or the complexity of force production increases. This suggests that the older adults' reduced finger-pinch force control reflects their relative inability to coordinate the force outputs of multiple fingers and to continually modulate both MU recruitment and firing rate.

The effect of ageing on the manner in which the digit forces are coordinated has been recently assessed in a number of studies. Using a two-digit finger-pinch task, Vaillancourt et al. (2002) observed no significant difference in inter-digit coupling or force control between young and older adults. This contrasts with Keogh et al. (2006) and Shim et al. (2004) who both reported a significant age-related decrease in force control and altered inter-digit coupling patterns for older adults during three- and five-digit finger-pinch tasks, respectively. In both of these studies, the difference in the digit force coupling was characterised by the older adults reducing both the relative contribution of the medial finger(s) to total force and the degree of co-variation (coupling) between the fingers' force outputs. Age-related differences in a number of inter-digit coordination measures have also been found in multi-finger finger pressing tasks (Shinohara et al., 2003; Shinohara et al., 2004). These results further support the view that the reduced force control of older adults reflects, at least in part a reduced ability to coordinate the force outputs of multiple fingers, i.e. to solve the degree of freedom problem.

Resistance-training adaptations in older adults

Numerous studies have assessed the effect of resistance-training on muscle capacity and function in older adults (Alexander, Gross, Medell, & Hofmeyer, 2001; Galganski et al., 1993; Hakkinen, Alen, Kallinen, Newton, & Kraemer, 2000; Hakkinen et al., 1998; Keen et al., 1994; Lord, Ward, Williams, & Strudwick, 1995; Schlicht, Camaione, & Owen, 2001; Taaffe, Pruitt, Pyka, Guido, & Marcus, 1996). These studies have typically shown significant training-related increases in measures of muscle capacity such as muscular strength and power. Although many of these studies have also reported significant improvements in functional performance as assessed during activities of daily living such as postural stability during upright stance, gait and sit to stand, the magnitude of these changes are generally not as pronounced as that for strength or power (Alexander et al., 2001; Lord et al., 1995; Schlicht et al., 2001). This may reflect the fact that performance in these activities of daily living is dependent on other factors than just strength and muscular power (Fiatarone-Singh, 2002; Grabiner & Enoka, 1995; Keogh, 2003; Lord, Murray, Chapman, Munro, & Tiedemann, 2002). The greater change in strength than functional performance may also relate to the principle of specificity which states that the transfer of training-related gains is greater the more similar the training and testing (transfer) task (Carroll, Riek, & Carson, 2001; Keogh, 2003; Wilson, Murphy, & Walshe, 1996). Nevertheless, the improvements in functional performance that older adults obtain from resistance-training typically exceeds that found for young adults (Barry & Carson, 2004; Fiatarone-Singh, 2002). This may reflect the overall decline in neuromuscular system function that characterises the ageing process.

Resistance-training by its ability to produce profound changes in neuromuscular and coordinative function (Barry & Carson, 2004; Behm, 1995; Carroll, Riek et al., 2001; Enoka, 1997a; Shepherd, 2001) may be able to significantly improve older adults' digit force control. This proposed improvement in force control could be mediated, at least in part by a reduction in MU firing rate variability or common MU modulation (Knight & Kamen, 2004; Kornatz, Christou, & Enoka, 2005) or through improved intra- and inter-muscular coordination (Bernardi, Solomonow, Nguyen, Smith, & Baratta, 1996; Carroll, Barry, Riek, & Carson, 2001). However, only three published studies have assessed the effect of resistance-training on the digit force control capabilities of older adults.

Effect of training on force control in older adults

Significant improvements in the digit force control capabilities of older adults have been reported as a result of strength- (Bilodeau et al., 2000; Keen et al., 1994) and coordination-training (Ranganathan, Siemionow, Saugen, Liu, & Yue, 2001). The strength-training programs performed by the subjects in the studies of Bilodeau et al. (2000) and Keen et al. (1994) were very similar. Both strength-training studies had their subjects perform three training sessions per week, with each session involving six sets of ten index finger abduction repetitions at 80% of the one repetition maximum (1RM). The only difference in these strength-training programs was their durations, being four and twelve weeks, respectively. The coordination-training program utilised by Ranganathan, Siemionow, Saugen et al. (2001) lasted for eight weeks, involving six sessions per week with each session lasting for ten minutes. The coordination-training program consisted of a ball manipulation task where the subjects used their thumb and fingers to simultaneously rotate two 150 g metal balls around the palm of one hand in both a clockwise and anti-clockwise direction.

The results of these three training studies would appear to indicate that resistance-training is an effective intervention for improving digit force control in older adults. However, due to the design of these studies it is not entirely clear if resistance-training can: 1) improve force control in commonly performed activities requiring the coordinated activity of multiple digit forces and muscles; and 2) produce a general adaptive response, whereby force control would be improved in tasks not specifically performed in training; and 3) improve force control during contractions of moderate or high intensity.

The significant improvements in force control reported by Bilodeau et al. (2000) and Keen et al. (1994) were observed in isometric index finger abduction force production tasks at forces ≤20% MVC. As the training and transfer tasks used in these two studies both involved isolated index finger abduction contractions, it is unclear based on these results whether resistance-training can significantly improve older adults' digit force control in tasks that involve a number of digits and agonist/antagonist muscles. This is an important consideration as all grasping movements require the coordinated activity of multiple digit forces and muscles (Carmeli et al., 2003; Maier & Hepp-Reymond, 1995; Schieber & Santello, 2004). It is also unknown based on the results of these studies whether resistance-training can significantly improve the force control capabilities of older adults in tasks that were not specifically practiced in training. Such a generality of response would be a very important finding, as it may not be feasible for older adults to practice every activity of daily living in which an age-related loss of digit force control reduces their performance (Barry & Carson, 2004).

In an attempt to overcome some of the limitations of the previous studies, Ranganathan, Siemionow, Saugen et al. (2001) assessed the effects of ball manipulation training on the finger-pinch force control of older adults Significant improvements in force control were observed at a range of relative (5%, 10% and 20% MVC) and absolute (2.5 N, 4 N and 8 N) loads regardless of whether the pinch task involved the thumb and index finger or the thumb and middle finger. This result is an important finding as it extends that of Bilodeau et al. (2000) and Keen et al. (1994) by demonstrating that resistance-training can significantly improve older adults' force control in commonly performed activities of daily living that require the coordination of numerous digit forces and muscles.

In their conclusions, Ranganathan, Siemionow, Saugen et al. (2001) suggested that their training and transfer tasks were completely different, and therefore that their results also demonstrated a general overall improvement in force control. Closer inspection of the ball manipulation training task used in training by Ranganathan, Siemionow, Saugen et al. (2001) however indicated that it required extensive use of finger-pinching motions. Consequently, even the results of Ranganathan, Siemionow, Saugen et al. (2001) are unable to clearly demonstrate a general force control adaptive response in older adults, whereby an overall training-related improvement in digit force control would be observed in transfer tasks that did not resemble those practiced in training.

The generality of older adults' force control response to resistance-training is further clouded by the fact that the improvements have only been observed when producing forces of up to 20% MVC (Bilodeau et al., 2000; Keen et al., 1994; Ranganathan, Siemionow, Saugen et al., 2001). The significant training-related improvement in force control for older adults at low but not moderate or high forces appears consistent with the literature for the effect of ageing on digit force control, whereby the age-related decline in force control and hence potential for improvement was greater at low than moderate or high forces (Keen et al., 1994; Laidlaw et al., 2000; Vaillancourt et al., 2003). However, it must be acknowledged that the apparent inability of resistance-training to improve older adults' force control at higher forces may just reflect the fact that the training studies have focused on the control of low-level forces, with only Keen et al. (1994) assessing changes in force control above and below 20% MVC. This suggests that further insight into the generality of force control response that older adults can obtain from resistance-training requires assessing the effect of training on force control at a variety of force levels.

The findings of Kornatz and colleagues (2005), while not actually assessing changes in digit force control (and hence not directly applicable to this review), also suggest that resistance-training may play a role in improving the force control and hand function of older adults. Kornatz et al. (2005) had ten older adults perform six weeks of training, this involved two weeks of light-load (10% 1RM) followed by four weeks of heavy-load (70% 1RM) index finger abduction exercise. This training resulted in significant reductions in the older adults' finger acceleration (somewhat analogous to force control) during resisted eccentric and concentric contractions as well as significant improvements in Purdue pegboard test performance. Even though no direct measure of force control were assessed, these findings are of considerable interest as they showed a significant improvement in hand function in a task (Purdue pegboard test), that required the coordinated activity of multiple fingers and agonist/antagonist muscles but was not practiced in training.

Future directions

In order to better understand the mechanisms underlying the reduced digit force control of older adults and how to design more effective physical training programs to improve their force control, future studies should utilise more challenging, real-world transfer tasks that require the production of force from multiple fingers. These studies should record the force output of all the digits involved in these tasks and if possible the EMG activity of the primary agonist and/or antagonist muscles. This approach will allow greater insight into how the ageing and training processes may affect the ability to control the force output of multiple digits and the activity of multiple muscles. Further, future training studies should alter a range of program design variables e.g. exercise selection, set and repetition ranges, training frequency etc in order to determine the optimal form of resistance-training to improve force control in older adults.

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Table 1: Effect of age on finger-pinch force control.

Study	Digits Used	Visual Feedback	Load Assessed	Force Measure	Age Difference
Christou et al. (2004)	Th and IF	Yes	2% MVC	CV	Older > Young
Cole (1991)	Th and IF	No	1.5 N	SD	Older > Young
Cole and Beck (1994)	Th and IF	Yes	0.49 N, 2.25 N and 10.5 N	CV	NS
Cole et al. (1999)	Th and IF	No	2 N and 4 N	CV	NS
Keogh et al. (2006)	Th, IF and MF	Yes	20% and 40% MVC (constant and sinusoidal)	CV and RMS	Older > Young
Kinsohita and Francis (1996)	Th and IF	No	3 N	SD	Older > Young
Lazarus and Haynes (1997)	All five digits	Yes	20-60% MVC (sinusoidal)	RMS	Older > Young

Ranganathan, Siemionow and Saugen et al. (2001)	Th and IF, Th and MF	Yes	5%, 10% and 20% MVC 2.5 N, 4 N and 8 N	SD and CV	Older > Young
Shim et al. (2004)	All five digits	Yes	0-20% MVC (ramp)	RMS	Older > Young
Vaillancourt et al. (2001b)	Th and IF	Yes	5%, 25% and 50% MVC	SD and RMS	NS
Vaillancourt et al. (2002)	Th and IF	Yes	5%, 25% and 50% MVC	SD and RMS	NS

Th = thumb, IF = index finger, MF = middle finger, MVC = maximum voluntary contraction, CV = coefficient of variation (relative force variability), SD = standard deviation (absolute force variability), RMS = root mean square error (targeting error), NS = no significant difference. Note: All loads were constant except where noted.