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Review

Effects of age on force steadiness: A literature review and meta-analysis

Nathalie M.C.W. Oomen^{a,b}, Jaap H. van Dieën^{a,*}^a MOVE Research Institute Amsterdam, Department of Human Movement Sciences, Vrije Universiteit Amsterdam, Van der Boerhorststraat 9, 1081 BT Amsterdam, The Netherlands^b Current Address: Department of Kinesiology, Faculty of Applied Health Sciences, University of Waterloo, 200 University Ave W, Waterloo, ON N2L 3G1, Canada

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ABSTRACT

The variability of force is indicative of the biological variability inherent in the human motor system. Previous literature showed inconsistent findings of the effect of age on the variability of force and hence a systematic review was performed. Twenty studies were included in this systematic review, of which twelve provided sufficient data to determine effect sizes for the effect of age. After determining the pooled effect size, the effect of sample size on dichotomized effect sizes (significant vs. non-significant) was determined. Also, the effect of possible determinants, age difference between age groups, dominance of investigated limb, muscle group, muscle location (proximal vs. distal and upper vs. lower extremity) and target force level on effect size (categorized as small, medium, or large) were investigated. A large pooled effect size of age was found ($r_{\text{total}} = 0.67$, 95% CI [0.61; 0.72]). No relation between sample size and effect size significance was found, indicative of no lack of power in the studies reviewed. No relations were found of associations between age difference, upper vs. lower extremity muscle location, and dominance and effect size. Significant relations of effect size with muscle group, proximal vs. distal muscle location and target force level were found. Also, an interaction effect of muscle group and target force level was suggested. The meta-analysis results are in line with motor unit loss as the main cause of the effect of ageing on force steadiness and this effect can partially explain decreased motor performance associated with ageing.

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* Corresponding author.

E-mail address: j.van.dieen@vu.nl (J.H. van Dieën).

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1. Introduction

Behavioral variability is inherent to biology. Traditionally, this variability was seen as the result of noise arising within the system or its environment. Similarly, variability of motor output in humans is commonly considered a result of neuromuscular noise and environmental influences. Neuromuscular noise is viewed as a limiting factor in the control of the human motor system. Following this line of reasoning, neuromuscular noise or its effects should be minimized to optimize performance (e.g. [Selen et al., 2006](#)). However, variability of motor output has also been interpreted as beneficial, as it may facilitate learning and coping with variable environmental and task demands ([Moseley and Hodges, 2006](#); [Newell and Corcos, 1993](#)). In addition, motor variability may promote variation in physical loading, which could prevent musculoskeletal overuse injuries ([Srinivasan and Mathiassen, 2012](#)).

Variability in the motor system is apparent in muscle force output. This is usually assessed during standardized submaximal isometric contractions, at an imposed constant target force ([Carville et al., 2007](#); [Marmon et al., 2011a, 2011b](#)). The actual force will fluctuate around an average value and the magnitude of this variability can be quantified as the standard deviation, or as the coefficient of variation (ratio of standard deviation to the mean) of the measured force, to quantify the (un-) steadiness of force production ([Enoka et al., 2003](#); [Marmon et al., 2011a](#)).

Force steadiness has been investigated in both upper and lower limbs (e.g. [Carville et al., 2007](#); [Marmon et al., 2011a](#)) and in different populations, such as young and old adults (e.g. [Enoka et al., 2003](#)). For both extremities, some studies have shown that older adults show a decreased steadiness in comparison to young adults ([Carville et al., 2007](#); [Enoka et al., 2003](#)). If force variability is a limiting factor in motor control, this increased variability may be one of the factors underlying decreased performance in many motor tasks with ageing. However, other studies did not reveal age effects on force steadiness ([Carville et al., 2006](#); [Graves et al., 2000](#); [Shinohara et al., 2005](#)). Several factors may account for differences in outcomes between studies, ranging from statistical factors (most importantly the number of subjects), demographic characteristics (e.g. the age differences between groups tested, physical activity levels), to task related factors, such as muscle group tested, and target force level ([Enoka et al., 2003](#)).

To determine whether an age effect on force steadiness indeed exists and to assess determinants of the effects of age, we performed a systematic review and meta-analysis of studies comparing force steadiness between old and young adults. We addressed the following three questions:

- 1 Does age have a significant effect on force steadiness after pooling data retrieved from the literature?

- 2 Are inconsistencies in literature caused by differences in sample size between studies, or in other words could a lack of study power explain negative results in some studies?
- 3 Are consistency and size of effects of age on force steadiness dependent on the age difference between groups included in the studies, the muscle group studied, or the target force imposed?

2. Methods

2.1. Literature search and inclusion criteria

Relevant literature was searched in Pubmed at April 18th 2014. Search terms used were (force OR muscle OR strength OR motor output) AND (steadiness OR fluctuations OR variability) AND (ag* OR elder* OR old*). The results of the search were examined by title and if the article seemed relevant, the abstract was screened. If the article was still assumed to be relevant, the article was obtained as full text and read to confirm the following inclusion criteria:

- 1 Force steadiness task: performance of a submaximal continuous isometric contraction with upper or lower extremity muscles to achieve a constant target force.
- 2 Target force is imposed relative to the subjects' Maximal Voluntary Contraction (MVC). Given the fact that muscle strength can be affected by age ([Frontera et al., 2000](#)), and since muscle strength can affect force steadiness at a given absolute force level ([Christou et al., 2002](#)), comparison between age groups at the same absolute force level could be confounded.
- 3 Coefficient of variation (CV) of force is reported as the outcome measure of force steadiness. Since the standard deviation of force produced increases approximately linearly with force produced ([Jones et al., 2002](#)), the CV allows comparison between studies using different target force levels.
- 4 Visual information on the target force and force produced was available during (at least a part of) the trial. Only data referring to (parts of) trials with visual feedback were used for the present review, because the number of studies on force steadiness without vision or with decreased visual feedback was not sufficient for a meta-analysis.
- 5 Force steadiness was compared between at least two different adult age groups (e.g. young and old adults).

2.2. Effect size calculations

To compare the differences in force steadiness between young and old adults among studies, effect sizes for all comparisons made between age groups were calculated from the data presented in the study, or in case of missing data, from data provided by the corresponding authors. Effect sizes were expressed as Pearson's correlation coefficient r , calculated from the t statistic ([Field, 2009](#); Sections 9.4.6 and 9.5.1). Furthermore, to estimate the 95% confi-

dence interval (CI) of the effect size, correlation coefficients were transformed into z-scores, 95% CI were calculated and transformed back to the CI of the correlation coefficient (Field, 2009; sections 6.3.3 and 6.3.4). To obtain pooled estimates for sub-groups of comparisons between age groups and across all comparisons made, weighted mean z-scores and standard errors were calculated and transformed to correlation coefficients to express the effect size and its corresponding CI. Pooled estimates were not determined for sub-groups which contained only one comparison and instead original r values with CIs are reported. Effect sizes were interpreted according to Cohen (1988, 1992): $r \geq 0.10$, small effect; $r \geq 0.30$, medium effect; $r \geq 0.50$, large effect.

2.3. Determinants of effect size

To assess potential causes of inconsistencies between studies we first assessed whether differences in sample size between studies could account for (not) finding significant differences between age groups. Effects were dichotomized into significant and non-significant, according to the significance level of the z-score for the effect size with an alpha level of 0.05 (Field, 2009; section 6.3.3). A Mann Whitney test was used to determine if sample sizes differed between significant and non-significant comparisons.

Subsequently, we analyzed the association between effect sizes and potential determinants of the effect sizes. Potential determinants investigated were: age difference, dominance, muscle group, muscle location (proximal vs distal and upper vs lower extremity), and target force level. Effect sizes for all comparisons were categorized into small, medium or large as described above, while effects size values smaller than 0.1 were also categorized as small. These categories were compared with respect to the potential determinants using Chi-square tests for nominal determinants or Kruskal-Wallis ANOVAs for ordinal determinants. Significance of Chi-square values was assessed using the exact probability of the Fisher's Exact test, if the majority of the cells had a count less than 5. Standardized residuals were used to locate categories with significant differences compared to the other categories.

3. Results

3.1. Inclusion

The initial search yielded 1280 hits of which 69 studies appeared relevant based on title, this number was reduced to 36 after examining abstracts. The latter 36 papers were read to check the inclusion criteria, which resulted in initial inclusion of eighteen studies. The references of these initially included studies were screened to correct for missed relevant studies, which led to the additional inclusion of two studies. These were also screened for relevant references, but this yielded no new results. In total twenty studies were included in the review. We provide an overview of the study characteristics below and a summary in Table 1. Twelve of the twenty studies provided sufficient data (in six cases after consulting the corresponding author) to allow estimation of the effect size of age. These studies have been highlighted in Table 1.

3.1.1. Demographic properties

Half of the studies contained an approximately equal distribution over males and females within each age group. However, some studies contained markedly more females than males (old group in Marmon et al. (2011b); all groups in Carville et al. (2007); young group in Burnett et al., 2000). Other studies included only men (Kouzaki and Shinohara, 2010; Tracy et al., 2007b), or only women (Bazzucchi et al., 2004; Carville et al., 2006; Dewhurst et al., 2007). Two studies provided no information on sex distribution of their study population (Galganski et al., 1993; Tracy et al., 2007b). The

total population included in this review appears to reflect a fairly equal distribution over males and females.

All studies included participants who were considered healthy. However, Ranganathan et al. (2001) reported that a few older participants suffered from mild arthritis of the hand or mild hypertension, but this did not affect their activities of daily living. Moreover, two studies (Sosnoff and Newell, 2006a, 2011) included only active old adults who lived independently, were able to walk without an assistive device and reported no falls in the preceding year. Many studies reported the physical activity of participants as sedentary to moderately active (Bazzucchi et al., 2004; Carville et al., 2006; Semmler et al., 2000; Shinohara et al., 2005; Tracy et al., 2007a, 2007b; Tracy and Enoka, 2002; Dewhurst et al., 2007). Some of these studies excluded participants with more than moderate physical activity during at least the preceding year, which was defined as more than three hours per week of exercise at a moderate intensity and strength training (Tracy et al., 2007a,b; Tracy and Enoka, 2002). One study excluded participants that had performed resistance training in the previous six months (Graves et al., 2000). So, overall both the young and old age groups studied were healthy and active, but not specifically trained.

3.1.2. Sample size

The total sample size of the included studies ranged from 16 to 122 participants. The distribution was clearly skewed, as the second largest study (Ranganathan et al., 2001) involved less than half ($n = 55$) of the participants of the largest study (Carville et al., 2007). In all but two studies, the number of participants was approximately equally divided over the groups. These two exceptions included almost twice as many older than young participants (Laidlaw et al., 2000; Sosnoff and Newell, 2006a). One study did not report the distribution of participants over the two age groups (Galganski et al., 1993). The large range of sample sizes over the included studies may indicate large differences in statistical power between studies.

3.1.3. Age groups

All the studies contained one group of young adults, with a mean age between twenty-one and twenty-nine years and at least one group of old adults, with a mean age between sixty-five and eighty-two years. The majority of studies compared one older to a young group. However, five studies included an additional age group. Apart from the young and old group, one study included a middle-aged group (Marmon et al., 2011b). Data on this age group were excluded from the remainder of this review. Four other studies included two old groups. Two studies made a distinction among older groups based on age: a sixty to sixty-nine years old group was distinguished from a seventy to seventy-nine years old group (Sosnoff and Newell, 2011) and a sixty-four to sixty-nine years old group was distinguished from a seventy-five to ninety years old group (Vaillancourt et al., 2003). Two other studies made a distinction based on medical data: fallers were distinguished from non-fallers within the old group (Carville et al., 2007) and older women were classified based on receiving hormone replacement therapy or not (Carville et al., 2006). When data on two older groups were reported we considered this as two separate comparisons with young adults in our analyses.

3.1.4. Muscle groups

The included studies assessed the isometric force steadiness of several different muscle groups. Ten studies tested the index finger abductors (IFA) (Burnett et al., 2000; Galganski et al., 1993; Laidlaw et al., 2000; Marmon et al., 2011b; Semmler et al., 2000; Shinohara et al., 2005; Sosnoff and Newell, 2006a, 2011; Tracy et al., 2007b; Vaillancourt et al., 2003). Six studies tested the knee extensor muscles (KE) (Bazzucchi et al., 2004; Carville et al., 2006, 2007;

Table 1

Summary of the included studies on study population, force steadiness task, and results. y=years in mean $\pm$ standard deviation; F=females; M=males; MVC=Maximal Voluntary Contraction; CV=Coefficient(s) of Variation=(standard deviation/mean* 100%); *¹ definition of faller: at least one fall in the previous year for medically unexplained reasons; *²HRT = hormone replacement therapy.

Study	Study Population	Force steadiness task	Results
Sosnoff and Newell (2011)	16 young (24.9 $\pm$ 3.8 y; 9 M, 7F) and 16 sixty to sixty-nine years old (65.7 $\pm$ 3.1 y; 8 M, 8F) and 16 seventy to seventy-nine years old (75.2 $\pm$ 2.7 y; 7 M, 9F) adults	Dominant isometric index finger abduction, two-digit isometric pinch (index finger against the thumb) and three-digit isometric pinch (index and middle fingers against the thumb) at 5% MVC.	Main effect of age in all three tasks (all $p < 0.05$). CV of index finger abduction force was greater in both older groups than the young group. CV of two-digit pinch was only greater in the sixty to sixty-nine years old group compared to the young group. CV of three-digit pinch was only greater in the seventy to seventy-nine years old group compared to the young group.
Marmon et al. (2011b)	25 young (25.8 $\pm$ 4.4 y; 14 M, 11F), 25 middle-aged (50.6 $\pm$ 5.6 y; 8 M, 17F) and 25 old (74.5 $\pm$ 6.3 y; 8 M, 17F) adults	Dominant and non-dominant isometric index finger abduction and two-digit isometric pinch (index finger against the thumb) at 5% MVC. Data of both extremities were combined.	CV was larger for old adults compared to both young and middle-aged adults for both the two-digit pinch ($p \leq 0.003$) and index finger abduction ($p \leq 0.001$) tasks. CV was similar for the young and middle-aged adults for both tasks ($p \geq 0.09$).
Kouzaki and Shinohara (2010)	20 young men (28.1 $\pm$ 4.0 y) and 20 old men (69.7 $\pm$ 2.8 y)	Dominant (right) isometric ankle plantar flexion at 2.5, 5, 10, 15 and 20% MVC.	CV of plantar flexion force was larger in old than in young men ($p < 0.05$) at 2.5 and 5% MVC, but not at 10, 15 and 20% MVC.
Tracy et al. (2007a)	22 young (22.9 $\pm$ 3.3 y) and 23 old (74.0 $\pm$ 7.1) adults	Non-dominant isometric elbow flexion and knee extension at 2.5, 30 and 65% MVC.	CV was larger for old compared to young adults at 2.5% MVC, and smaller for old compared to young adults at 30 ($p < 0.001$) and 65% MVC ($p < 0.001$) for both the elbow flexors and knee extensors.
Carville et al. (2007)	44 young (29.3 $\pm$ 0.6 y; 18 M, 26F) and 78 older adults: 34 fallers (70.6 $\pm$ 4.6 y; 5 M, 29F) and 44 non-fallers* ¹ (75.9 $\pm$ 0.6; 15 M, 29F)	Unilateral isometric knee extension of both legs at 10, 25 and 50% MVC. Data of both extremities were combined.	CV was larger in the fallers compared to both the young adults and non-fallers (both $p < 0.0001$) at all targets.
Dewhurst et al. (2007)	15 young women (23.6 $\pm$ 3.4 y) and 11 older women (68.6 $\pm$ 5.7 y)	Dominant isometric ankle dorsiflexion at 5, 10 and 15% MVC.	CV of force was higher for the old adults compared to the young adults at all target levels ($p < 0.01$).
Sosnoff and Newell (2006a)	15 young (24.9 $\pm$ 3.8 y; 9 M, 6F) and 33 old (70.9 $\pm$ 5.6 y; 15 M, 18F) participants	Dominant isometric index finger abduction at 5 and 25% MVC.	A main effect of age was found ($p < 0.05$). CV in old adults was larger than in young adults.
Tracy (2007)	11 young (22.7 $\pm$ 2.7 y; 6 M, 5F) and 10 old (72.8 $\pm$ 5.5 y; 5 M, 5F) adults	Left isometric ankle dorsal flexion and plantar flexion at 2.5, 5, 10, 30, 50 and 80% MVC.	No differences in dorsal flexor CV were found between the groups. CV of plantar flexor force was larger for old compared to young adults at 2.5 ($p = 0.03$) and 5% MVC ($p = 0.04$), similar at 10, 50 and 80% MVC and larger for young compared to old adults at 30% MVC ($p = 0.012$).
Bazzucchi et al. (2004)	8 young (24.2 $\pm$ 4.2 y) and 8 old (70.6 $\pm$ 2.6 y) women	Dominant isometric elbow flexion and knee extension at 20, 50 and 80% MVC.	CV was larger in old than in young women ($p < 0.05$) at 80% for both elbow flexion and knee extension, and only at 20% for elbow flexion ($p < 0.05$).
Tracy et al. (2007b)	10 young (21.7 $\pm$ 3.4 y) and 10 old (72.1 $\pm$ 3.9 y) men	Non-dominant (left) isometric index finger abduction, elbow flexion and knee extension at 2, 5, 10, 30 and 50% MVC.	Pooled across muscles and target levels, the CV was similar for young and old men ($p = 0.90$). The CV was greater for old compared to young men ($p = 0.04$) for the index finger abduction only at the 2% MVC.
Carville et al. (2006)	16 young (27.4 $\pm$ 5.6 y) and 29 postmenopausal women of which 15 were receiving HRT* ² (68.1 $\pm$ 5.3 y) and 14 not (70.5 $\pm$ 5.8 y)	Isometric knee extension of both legs at 10, 25 and 50% MVC. Data of both extremities were combined.	No differences in CV were found among the three age groups.
Shinohara et al. (2005)	10 young (24.1 $\pm$ 5.3 y; 5 M, 5F) and 10 old (72.5 $\pm$ 4.9 y; 5 M, 5F) adults	Isometric index finger abduction of both hands at 2.5, 10 and 40% MVC. Data of both extremities were combined.	No differences in CV were found between age groups.
Vaillancourt et al. (2003)	10 young (22 $\pm$ 1 y; 5 M, 5F), 10 sixty-four to sixty-nine years old (67 $\pm$ 2 y; 5 M, 5F) and 10 seventy-five to ninety years old (82 $\pm$ 5 y; 5 M, 5F) adults	Dominant isometric index finger abduction at 5, 10, 20 and 40% MVC.	Main effects of age were found at each target level (all $p < 0.01$), with a sequence of young < sixty-four to sixty-nine years old < seventy-five to ninety years old.
Tracy and Enoka (2002)	20 young (22.1 $\pm$ 2.2 y; 10 M, 10F) and 20 old (71.5 $\pm$ 4.3 y; 10 M, 10F) adults	Left isometric knee extension at 2, 5, 10 and 50% MVC.	CV of knee extension force was significantly larger for old adults compared to young adults at 2, 5 and 10% MVC ($p < 0.05$), but not at 50%.
Burnett et al. (2000)	14 young (23 $\pm$ 0.9; 5 M, 9F) and 15 old (74 $\pm$ 1.5 y; 8 M, 7F) adults	Non-dominant (left) isometric index finger abduction at 2.5, 5, 20, 50 and 75% MVC.	CV was greater in old adults compared to young adults at all target forces (all $p < 0.05$), except at 20% MVC.
Semmler et al. (2000)	11 young (24.1 $\pm$ 4.1 y; 5 M, 6F) and 14 old (70.4 $\pm$ 5.9 y; 8 M, 6F) adults	Non-dominant (left) isometric index finger abduction at 2.5, 5, 7.5 and 10% MVC	CV was larger in old adults compared to young adults at 2.5 and 5% MVC ($p < 0.05$), not at 7.5 and 10% MVC.
Graves et al. (2000)	17 young (22.9 $\pm$ 3.5 y; 7 M, 10F) and 15 old (71.2 $\pm$ 7.8 y; 7 M, 8F) adults	Non-dominant (left) isometric elbow flexion at 5, 10, 20, 35, 50 and 65% MVC.	No differences in CV were found between the age groups.
Laidlaw et al. (2000)	8 young (26.6 $\pm$ 0.57 y; 4 M, 4F) and 14 old (73.4 $\pm$ 1.63 y; 6 M, 8F) adults	Non-dominant (left) isometric index finger abduction at 2.5, 5, 7.5 and 10% MVC.	CV was larger for old adults compared to young adults at all target levels.
Galganski et al. (1993)	22 (16 M, 6F) subjects divided into young (28 y) and old adults (67 y)	Non-dominant (left) isometric index finger abduction at 5, 20, 35, 50% MVC.	CV was larger for old adults compared to young adults at all target levels.
Ranganathan et al. (2001)	27 young (27.7 y; 13 M, 14F) and 28 older (70.5 y; 12 M, 16F) adults	Dominant (right) submaximal finger pinch (the thumb against either the index or middle finger) was exerted at 5, 10, 20% MVC.	CV was larger for old adults compared to young adults at both 5% and 10% MVC for both the index (both $p < 0.001$) and middle finger-thumb pairs ($p < 0.001$ and $p < 0.05$).

Tracy et al., 2007a, 2007b; Tracy and Enoka, 2002) and four tested the elbow flexor muscles (EF) (Bazzucchi et al., 2004; Graves et al., 2000; Tracy et al., 2007a, 2007b). Three studies tested pinch force between the index finger and the thumb (TI) (Marmon et al., 2011b; Ranganathan et al., 2001; Sosnoff and Newell, 2011), and one tested the pinch force between index and middle fingers and the thumb (TM) (Sosnoff and Newell, 2011). Two studies tested the ankle plantar flexor muscles (PF) (Kouzaki and Shinohara, 2010; Tracy, 2007). Finally, one study tested the ankle dorsal flexors (DF) (Dewhurst et al., 2007). For dichotomization into proximal and distal, IFA, TI, TM, PF and DF were considered distal muscle groups and KE, EF were considered proximal muscle groups. For dichotomization into upper and lower extremity muscles, KE, PF and DF were considered lower extremity muscle groups and EF, IFA, TI and TM were considered upper extremity muscle groups.

The majority of the study assessed steadiness on one side of the body, while some studies assessed both sides (Carville et al., 2007, 2006; Marmon et al., 2011b; Shinohara et al., 2005). The studies assessing only one side, tested the dominant side in eight cases (Bazzucchi et al., 2004; Kouzaki and Shinohara, 2010; Ranganathan et al., 2001; Shinohara et al., 2005; Sosnoff and Newell, 2006a, 2011; Vaillancourt et al., 2003; Dewhurst et al., 2007) and the non-dominant side in seven cases (Burnett et al., 2000; Galganski et al., 1993; Graves et al., 2000; Laidlaw et al., 2000; Semmler et al., 2000; Tracy et al., 2007a, 2007b). Two studies tested only the left side, without reporting dominance (Tracy, 2007; Tracy and Enoka, 2002). The total set of comparisons included in this review thus represents a reasonable distribution over dominant and non-dominant extremities.

3.1.5. Target force levels

Target forces imposed in the studies ranged from 2 to 80 MVC, with many studies comprising tests at different force levels. A detailed overview can be found in Table 1. We arbitrarily categorized target levels as low between 2 and 10% MVC, as medium between 15 and 35% MVC and as high between 40 and 80% MVC.

3.2. Effect of age on force steadiness

Twelve studies were used to determine effect sizes, yielding a total of fifty-seven estimates of age effects (Table 1). The effect sizes and their 95% confidence intervals (CI) are plotted in Fig. 1, in ascending order of target level, while muscles are distinguished by different symbols. Note that negative effects, i.e. larger CVs of force for young compared to older adults, were not found. A substantial number of the positive effects was, however, not significant, as indicated by the 95% CI crossing the abscissa. The pooled effect size of age over all comparisons was significant, with $r_{\text{total}} = 0.67$, 95% CI [0.61; 0.72]. The eight studies that were not included in the meta-analysis yielded significantly positive effects (higher CV in the old group) in fourteen, no significant effects in 34, and negative effects in only five of the 53 comparisons.

3.3. Effects of sample size

Although, a trend towards larger sample sizes for comparisons with a significant effect was observed, the difference in samples size between comparisons with significant (Mdn = 26, IQR = 18) and non-significant effects (Mdn = 32, IQR = 20) was not significant ($U = 303.00$; $z = -1.25$; $p = 0.212$).

Fig. 1. Effect sizes with 95% CI of force steadiness. The force steadiness outcomes are sorted in order of target level, the top effect size was obtained at the highest target level, while the bottom effect size was obtained at the lowest target level. Different muscle groups are indicated by different symbols, as shown in the legend: KE: knee extensors; EF: elbow flexors; PF: plantar flexors; DF: dorsal flexors; IFA: index finger abductors; TI: thumb index finger precision pinch.

3.4. Potential determinants of magnitude and consistency of age effects

3.4.1. Age difference

No significant difference was found in age difference between the effect size categories ($H = 0.36$; $p = 0.84$).

3.4.2. Muscle group

A significant association between muscle group and effect size was found ($\chi^2 = 24.15$; $p < 0.01$). Standardized residuals from the contingency table showed that this difference was determined by the EF muscle group showing a lower proportion of large effect sizes compared to the other muscle groups (standardized residual = -2.2). Effect size for the IFA muscle group tended to be large compared to other muscles but this effect was not significant as indicated by a standardized residual of 1.4.

Table 2

Pooled effect sizes and their respective 95% CI, expressed in correlation coefficient r . *1: this subgroup consisted of only one outcome, no pooling was executed.

Muscle group	Pooled effect size	95% CI
Knee extensors	0.72	0.62; 0.79
Elbow flexors	0.20	−0.12; 0.49
Plantar flexors	0.37	0.07; 0.61
Dorsal flexors	0.65	0.35; 0.83
Index finger abductors	0.79	0.72; 0.85
Thumb index finger precision pinch*1	0.54	0.31; 0.71

The pooled effect size for the IFA muscle was large ($r_{\text{pooled}} = 0.79$, 95% CI [0.72; 0.85]; see Table 2) and accounted for 62% of the total variance. This is supported by Fig. 1, showing that the majority of the CIs did not cross the abscissa, indicating that almost all effects were significant. The age comparisons for KE also showed a large effect ($r_{\text{pooled}} = 0.72$; 95% CI [0.62; 0.79]), accounting for 52% of the total variance. Fig. 1 shows that less than half of the CIs for KE crossed the abscissa, indicating that the literature is inconsistent with respect to force steadiness of this muscle group. The age comparisons for PF showed a medium effect ($r_{\text{pooled}} = 0.37$, 95% CI [0.07; 0.61]), accounting for 14% of the total variance. Fig. 1 shows a wide range of effects for this muscle group from large and significant to small and non-significant. The age comparison for DF showed a large effect ($r_{\text{pooled}} = 0.65$, 95% CI [0.35; 0.85]), accounting for 42% of the total variance. Fig. 1 shows only significant and large effect sizes. The age comparisons for EF showed a small effect ($r_{\text{pooled}} = 0.20$, 95% CI [−0.12; 0.49]), accounting for 4% of the total variance, with none of the comparisons for EF being significant (Fig. 1). The single comparison for TI showed a significant and large effect ($r = 0.54$, 95% CI [0.31; 0.71]), accounting for 29% of the total variance.

A significant association between effect size and proximal vs. distal muscle location was found ($\chi^2 = 12.13$; $p < 0.01$). Standardized residuals from the contingency table showed that this difference was determined by more large effect sizes in the distal muscles (standardized residual of 1.4) compared to the proximal muscles (standardized residual of −1.8). Also, proximal muscles showed a higher proportion of small effect sizes compared to distal muscles, however this difference was not significant according to the standardized residual of 1.5. No association between effect size and extremity (upper vs lower) was found ($\chi^2 = 1.56$; $p = 0.46$).

No association between effect size and dominance was found ($\chi^2 = 5.71$; $p = 0.22$).

3.4.3. Target force

A significant difference in target force level was found between the effect size categories ($H = 11.02$; $p < 0.01$), where large effect sizes were mainly found at low target levels. Up to 10% MVC only a few CIs of the effect size crossed the abscissa, indicating that most of the effects at the lowest target levels were significant. Pooled effect sizes at these low forces were large (Table 3). At 15% MVC and higher the effect sizes were still mainly large but, less consistent because half of the CIs of the effect size crossed the abscissa. From 40% MVC and higher effect sizes were mainly medium and even more inconsistent, because just more than half of the CIs of the effect size crossed the abscissa indicating a lack of significance. Fig. 1 shows that effects sizes above 10% MVC decreased albeit with inconsistencies between comparisons at different force levels. Overall, at target levels from 2 to 10% MVC effect size was large ($r_{\text{pooled}} = 0.72$, 95% CI [0.65; 0.78]) accounting for 52% of the variance, from 15 to 35% MVC the effect size was slightly lower, but still large ($r_{\text{pooled}} = 0.68$, 95% CI [0.55; 0.78]) accounting for 46% of the variance and effects were less consistent, and from 40 to 80% MVC the effect size was just below large ($r_{\text{pooled}} = 0.48$, 95% CI [0.29; 0.64]) accounting for 23% of the variance and the CI of this pooled effect size also indi-

Table 3

Pooled effect sizes and their respective 95% CI, expressed in correlation coefficient r . *1: this subgroup consisted of only one outcome, no pooling was executed.

Target level (%MVC)	Pooled effect size	95% CI
2*1	0.50	0.22; 0.70
2.5	0.85	0.68; 0.93
5	0.65	0.53; 0.75
7.5	0.76	0.31; 0.93
10	0.77	0.66; 0.85
15	0.55	0.11; 0.81
20	0.41	0.08; 0.66
25	0.90	0.80; 0.95
35	0.61	0.08; 0.87
40	0.15	−0.67; 0.80
50	0.47	0.24; 0.65
65*1	0.35	0.00; 0.62
75*1	0.85	0.70; 0.93
80	0.33	−0.53; 0.86

cates a larger variance in these effect sizes thereby indicating more non-significant effects.

3.4.4. Muscle group $\times$ target level

The results in Fig. 1 suggest an interaction between muscle group and target level. For IFA, no clear effect of target level was found, because at least 80% of the effects were significant across all three target ranges (2–10; 15–35; 40–80% MVC). However, for KE significant effects were found at low target levels but not consistently above 50% MVC. Similarly, for PF significant effects were found at the lowest target levels up to 5% MVC, while effects were not significant at target levels between 10 and 20% MVC. For DF, effects were large and significant over the entire target range, while for EF, effects were small and non-significant over the entire target range.

4. Discussion

4.1. Effect of age on force steadiness

In present review strong evidence was found for an effect of age on force steadiness, as the pooled effect size was large ($r_{\text{total}} = 0.67$, 95% CI [0.61; 0.72]), but variance in outcomes between comparisons made in the literature was large. Differences in statistical power, i.e. sample size, did not contribute to inconsistencies in the literature.

4.2. Possible determinants of effect size

From the analysis of the potential determinants, it can be concluded that lower versus upper extremity, age difference (over the range of age differences studied), and dominance did not influence effect size. With respect to age difference, it should be noted that the contrast between age groups was substantial in all included studies. Muscle group and location of the muscle group did determine effect size. The difference in age effects on force steadiness found between muscle groups is possibly partially caused by the fact that effects are larger in distal than proximal muscles, while age effects on muscles in upper and lower extremities did not appear to be different. Also, the age effect depends on the level of the target force, with larger effects at lower forces. Finally, an interaction effect of muscle group and target level appears to exist. Noticeable are the large effects found for the PF muscles at the lowest target levels, and for the KE muscles at low-to-medium target levels, while the IFA and DF showed effects over the entire target force range in contrast to EF which showed no effects over the entire target force range.

A previous narrative review suggested that the magnitude of the difference between young and old adults in force steadiness depends on the force capacity of the investigated muscle group

(Enoka et al., 2003). Studies on large muscle groups found no difference in steadiness between young and old, which could explain the lack of effect found in EF in present review. This is also in line with our finding of a larger effect size in distal muscles, which are typically smaller muscle groups (PF, DF, IFA and TI) compared to proximal muscle groups (KE and EF). In line with present review, Enoka et al. (2003) also observed that the difference between young and old adults was most apparent at low relative forces.

The CV of force has been suggested to show a non-monotonic relation with the target force, with the largest CV at 2.5% MVC, minimum values at intermediate forces, and moderate values at target forces greater than 50% MVC (Enoka et al., 2003). Only the notion of large force steadiness at low forces was substantiated in the present meta-analysis. Moreover, large effects were shown to occur up to 35% MVC (with an exception for 20% MVC: medium effect size), above which mainly medium and inconsistent effects were shown up to 80% MVC.

4.3. Physiological causes of observed effects

The increase in force variability with age may be explained by several mechanisms, including changes in motor unit numbers, motor unit synchronization, levels of antagonistic coactivation, peripheral feedback loops, visuomotor processing and motor unit discharge variability. Force variability was shown to be minimal when muscles are electrically stimulated (Jones et al., 2002), indicating that processes downstream from the motor neuron pool do not play a significant role. We will discuss each of the potential mechanisms below.

Motor unit reorganization which occurs with ageing, results in a decrease in the number of motor units in a muscle: alpha motor neurons are lost, which leads to reinnervation of some of the denervated muscle fibers by surviving motor neurons (Brown, 1972, 1973; Campbell et al., 1973). Consequently, more muscle fibers are innervated by the same motor neuron, resulting in larger motor units of the same fiber type (Larsson, 1995; Kanda and Hashizume, 1989; Lexell and Downham, 1991). Eventually, motor unit reorganization thus leads to fewer but larger and less spatially mixed motor units (Hepple and Rice, 2015). Because of this reorganization, large motor units are activated early, at lower force levels and at lower firing rates in elderly subjects compared to younger subjects, which makes the output of force more variable because the last recruited motor unit has the largest influence on the force variability (Selen et al., 2005). This effect of ageing is especially noticeable at low forces, where each motor unit has a large contribution to the net force (Fuglevand et al., 1993). Also, the effect of motor unit reorganization would be more pronounced in distal muscle groups compared to proximal muscle groups, because distal muscle groups tend to be smaller and the relative effect of motor unit reorganization would be larger (i.e. relative larger increase in muscle fibers per surviving motor unit).

Computer simulation predicts an increase in force fluctuations during submaximal isometric contractions when motor unit discharge is more synchronized (Yao et al., 2000). However, no increase in motor unit synchronization was found with an increase in force variability among old adults (Semmler et al., 2000). After reanalysis of the same data, based on motor unit coherence, a higher amplitude of common oscillatory inputs was revealed in old adults compared to young adults at low force levels (Semmler et al., 2003). However, a limitation of this study is that no medium-to-high force levels were investigated and thereby no conclusion can be drawn with regards to the potential dependence of the age effect on force level. Therefore, motor unit synchronization may explain the increase of force variability with ageing. However, it remains to be investigated whether this mechanism would explain the more pronounced effects at lower force levels and in distal muscles.

A simulation study indicated that increased antagonistic coactivation reduces kinematic variability, but it increases force variability in isometric contractions (Selen et al., 2005). Increased antagonistic coactivation has been associated with ageing (Hortobágyi and Devita, 2006). Although increased force variability in older adults was associated with coactivation in one study (Tracy and Enoka, 2002), this was not found in two other studies (Burnett et al., 2000; Kouzaki and Shinohara, 2010). Therefore, the potential role of antagonistic coactivation requires more study.

Imposing the same constant target force with two different methods revealed a difference in the frequency spectrum of the force and EMG signals, which was suggested to be related to peripheral feedback (Matthews and Muir, 1980). The first method consisted of maintaining a compliant spring at constant length, which required a constant joint angle, while the second method consisted of producing the same force against a rigid resistance. Force and EMG signals in the first method showed a sharp peak at 8 Hz, which disappeared with the second method while some power remained evenly spread over the 7.5 to 11.5 Hz band. A possible explanation for the difference found is that the stretch reflex loop would have much more effect in the former condition, where muscle fascicle length changes would be more pronounced (Vallbo and Wessberg, 1993). This interpretation is supported by studies that confirmed that distinct peaks in the force power spectrum around 8 Hz are caused by synchronization of motor unit firing (Christakos et al., 2006; Erimaki and Christakos, 1999). These studies also provided evidence that synchronization is caused by muscle spindle feedback associated with small fluctuations in muscle fascicle and spindle length that accompany force variations units. This component of force variability would increase with larger delays and gains of spindle feedback. Stretch reflexes delays have found to be longer with ageing (Dewhurst et al., 2005; Kido et al., 2004; Scaglioni et al., 2002; Chen et al., 2014; Chung et al., 2005). On the other hand, a slight decrease of the number of muscle spindles in a muscle with ageing has been found (Swash and Fox, 1972), and stretch reflex gains and H-reflex gains appear to be lower (Chung et al., 2005; Chen et al., 2014). In conclusion, given that age-related changes in gain and delay of the stretch reflex loop likely counteract each other in terms of causing oscillations in force output, this appears not to be a likely cause of the age effects on force variability. Moreover, the 8 Hz component of force variability is relatively small compared to the total power (Slifkin and Newell, 2000; Slifkin et al., 2000).

Since the studies included in our review used visual feedback of the force level produced, age-related changes in visuomotor processing may also account for changes in force variability. Force variability in the 0–2 Hz frequency band has been associated with visual feedback (Slifkin and Newell, 2000; Slifkin et al., 2000). When the frequency of visual feedback was reduced, a decrease in power was found in the 0–2 Hz frequency band of force variability (Slifkin et al., 2000). However, when visual feedback was completely removed no difference in absolute power was shown (Christou, 2005). Scaling of visual feedback has been shown to affect force variability (Sosnoff and Newell, 2006b). Old adults were found to have higher force variability compared to young adults, only at high resolution of visual feedback (Sosnoff and Newell, 2006b). This appears to contradict poor visual acuity of older adults as an explanation of the increase in force variability typically seen at low levels of force (where visual resolution is usually low). Old adults have longer minimal visual processing time compared to young adults (Sosnoff and Newell, 2006c) and artificially induced delays in visual feedback increase force variability (Sosnoff and Newell, 2007). However, while studies addressing visuomotor delays as a potential cause showed larger force variability in old than young adults, force variability was not associated with visual processing

time (Sosnoff and Newell, 2006b,c, 2007). On the other hand, two studies showed that reducing the amount of visual information (by changing a pursuit display into a compensatory display, see Ofori et al., 2010) reduced or even negated age-related differences in force variability between age groups (Ofori et al., 2010; Tracy et al., 2007a). In one of these studies this interaction effect was consistent across forces ranging from 5 to 20% MVC (Ofori et al., 2010); the other study found this interaction effect at 2.5% MVC, but not 30 and 65% MVC (Tracy et al., 2007a). Similarly, the difference in motor unit discharge variability between age groups was shown to disappear after removal of the visual feedback (Welsh et al., 2007). However, in this study no difference in force variability between young and old adults was found in the visual feedback condition. In summary, several studies show that visual feedback may modulate the decline in force steadiness with ageing. Moreover, the study by Tracy et al. (2007a) suggests that this effect may be more pronounced at low force levels, however another study by Sosnoff and Newell (2006b) contradicts differences in force variability at low force levels due to visuomotor processing. We excluded these studies from the review, given the low numbers and the use of widely different methods: of disturbing visual feedback (removal, resolution or delay). Given the fact that force variability without the presence of visual feedback would be more representative for daily-life function, this is a limitation of this review and more work is needed in this area.

Finally, increased motor unit discharge variability has been implicated as a cause of increased force variability with age (Enoka et al., 2003; Laidlaw et al., 2000; Moritz, 2005). Motor unit discharge variability is largest in the 1–2 Hz frequency band (Vaillancourt et al., 2002). Force variability has been shown to cross-correlate with motor unit firing rate variability in the 1–2 Hz band (De Luca et al., 1981). Variability in this frequency band is suggested to be caused by the common drive of the central nervous system (De Luca et al., 1981; De Luca and Erim, 1994, 2002) and hence of upstream processes such as discussed above, i.e., peripheral feedback and visuomotor processing. However, another contribution to variability in this frequency band is the alpha motor neuron's synaptic noise (Matthews, 1996). Results of computer simulations suggest that variability of the motor unit discharge rate has a larger effect on force variability than motor unit loss (Enoka et al., 2003). However, three experimental studies showed no difference in discharge rate variability between young and old adults, while they did find a difference in force variability (Galganski et al., 1993; Vaillancourt et al., 2003; Dewhurst et al., 2007). Therefore, the importance of motor unit discharge variability, and the upstream processes that affect it, for the age-related increase in force variability with ageing is unclear.

In conclusion, the causes of the increase in force variability under visual feedback with ageing require further study. A decreased motor unit number could not only explain the increase in force variability with ageing, but could also account for our finding that this increases is most pronounced at low force levels and in the smaller (distal) muscles.

4.4. Functional relevance of observed effects

A few studies have correlated performance on functional tasks to force steadiness. Two studies measured precision tasks of fingers and hand, in which time had to be minimized or movements had to be performed as accurate as possible (Marmon et al., 2011a, 2011b). In Marmon et al. (2011b) the performance of older adults was less good than in young adults, corresponding to the difference in force steadiness. Performance on two functional tasks was moderately correlated to index finger abduction and pinch steadiness, and multiple regression models predicting task performance included some of these outcomes and grip strength. However, correlations within

age groups were not assessed, so these findings should be interpreted with caution. In Marmon et al. (2011a) a single functional task was performed by a group of older adults, divided in a practice and a control group. The practice group was faster on the functional task and more steady in both index finger abduction and precision pinch. These studies provide support to the perception of variability as noise that should be minimized to optimize performance in precision tasks.

In contrast to the precision tasks discussed above, in non-precision tasks, variation may be beneficial, as it does not by definition limit task success. A study by Seynnes et al. (2005) addressed several tasks, of which the performance becomes limited at older age. In this study, regression models showed a higher variability of torque to predict a longer duration of chair rising (slower speed) and a lower endurance (covered vertical distance) and speed (time to ascend) in stair climbing. But using a similar set of tasks (chair rising, ascending/descending stairs and gait speed), this finding was not confirmed by Manini et al. (2005). Another study investigated the correlation between PF force steadiness and anterior-posterior center of pressure (CoP) steadiness during quiet stance, which is assumed to reflect the function of the balance control system (Kouzaki and Shinohara, 2010). Only force steadiness at low force levels (2.5 and 5% MVC) was related to CoP steadiness, while no relation was found at medium force levels (10, 15 and 20% MVC). Possibly related to this, a higher force variability was found in a group of older fallers group compared to young adults, while no difference was found between older non-fallers and young adults (Carville et al., 2007). These studies also support the hypothesis that variability limits successful task performance.

5. Conclusion

The present review shows a substantial effect of age on force steadiness in five out of six muscles for which sufficient data was available for meta-analysis. This effect is dependent on force level and is different between muscles. For target force level, there are generally large and consistent effects at the lowest force levels (<10% MVC), which decrease and become less consistent at moderate-to-high target levels. With respect to muscles, small distal muscles such as the index finger abductors show effects over the entire force range, and large, proximal muscles such as the knee extensors show effects only at target levels below 20%MVC. The pattern of effects is in line with motor unit loss as the main causes of the effect of ageing on force steadiness and this effect appears to have detrimental consequences for performance of functional tasks among elderly.

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