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Unintentional Force Drift After Visual Feedback Removal: Temporal Dynamics and Associations with Age

Michał Pawłowski

Department of Human Motor Behavior, Institute of Sport Sciences, Academy of Physical Education in Katowice, 40-065 Katowice, Poland; m.pawlowski@awf.katowice.pl

Abstract

When visual feedback is removed during sustained force production, force may gradually decline despite an unchanged instruction to maintain it. This phenomenon is known as unintentional force drift (UFD), but its temporal dynamics and relationship with age remain unclear. This study examined how UFD developed over time and whether its magnitude and temporal course were associated with age. This secondary analysis used data from 24 healthy adults aged 18–69 years originally collected to assess the reliability of UFD measurements. Participants completed six 20 s bilateral isometric elbow-flexion trials at 20% of maximal voluntary contraction, both with and without visual force feedback. Force drift was calculated from changes in force between the beginning and end of each trial. One-second intervals were used to examine the temporal dynamics of force loss, while associations with age were assessed using repeated-measures analysis of covariance and linear regression. Force drift was more negative without visual feedback than with feedback ($-9.78 \pm 7.02\%$ vs. $0.83 \pm 2.06\%$; $p < 0.001$). No statistically significant associations of age with UFD magnitude or its temporal dynamics were detected. After feedback removal, the group average force loss trajectory began to decline after a brief delay, changed almost linearly, and reached a plateau at approximately 9 s. The mean force-loss estimate after 10 s was close to the 20 s estimate, although agreement between these estimates varied across participants. UFD after visual feedback removal follows a structured temporal pattern, with most force loss occurring early and followed by relative stabilization. Within the present analysis, neither UFD magnitude nor its temporal course showed a substantial association with age. These findings provide a basis for further investigation into whether UFD measurement procedures can be simplified.

Keywords: force control; ageing; isometric contraction; motor control; bilateral force production

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1. Introduction

Effective motor control often requires continuous adjustment of force to the level needed for the intended movement, particularly when direct visual feedback is unavailable. In everyday activities such as holding a phone to the ear or gripping a handrail while using stairs, gaze is typically directed toward other aspects of movement performance rather than toward the force-production process itself. Force control therefore contributes to the safe and independent performance of many everyday activities. This is particularly relevant in the context of ageing: older adults generally show less steady control of sub-maximal force, and lower force steadiness has been associated with poorer manual dexterity, walking, and balance [1,2]. Visual feedback provides information about movement execution, allowing for rapid correction of force deviations that may compromise successful performance [3].

When this information is removed, force typically declines from the previously established level despite an unchanged instruction to maintain it [3,4]. This gradual and unintended loss of force is widely known as unintentional force drift (UFD) [3–5]. Remarkably, people are often unaware that their force is declining [6–8]. UFD appears to be a widespread phenomenon across different body segments, with force declines reported for the fingers, bilateral elbow flexors, and lower limbs [9–11]. UFD seems to develop gradually over time. In force-control research, temporal dynamics describe changes in force output throughout a task, including their timing, rate, stability, and variability. These dynamics have been examined using force trajectories, frequency-domain measures, signal complexity, and analyses of deterministic and stochastic components [12–14]. Such approaches can distinguish consistent patterns from short-term fluctuations and reveal information that cannot be captured by a single mean or endpoint value. In this context, ageing can be considered an important factor when examining how force is controlled over time. Even in healthy adults, ageing is accompanied by neuromuscular and sensory changes that may reduce the precision of force control [1]. These changes are reflected in less steady and less complex force output [1,13,14] and may be relevant to everyday activities that help maintain independence and quality of life [2].

Although force control is known to change with age, the relationship between age and UFD is still unclear. Therefore, the main aim of this study was to examine this relationship in healthy adults, considering both the magnitude and temporal dynamics of UFD.

Older adults generally show less precise force control and a reduced ability to adjust force output, particularly when visual information is limited [1,15]. A previous study also showed that UFD measurements were less reproducible and characterized by greater measurement error in older adults [9]. Together, these findings suggest that maintaining a previously established force level after visual feedback removal may become more difficult with age. It was hypothesized that older age would be associated with greater force loss in the absence of visual feedback.

Beyond its relationship with age, an important question concerns how UFD develops during the no-feedback condition. Previous studies have characterized UFD primarily through the total force loss or a single time constant describing only the overall decline [3–5]. These measures describe the magnitude and general time scale of UFD but do not show how the rate of force loss changes throughout the task or if the force stabilizes. Force-matching studies have also shown that force drift can briefly accelerate and then stabilize or even reverse [8,11]. Therefore, the second research question in the present study was whether the rate of force loss changed over time and whether the force eventually stabilized. It was hypothesized that force loss would slow over time and eventually reach a plateau.

In cases where force loss reaches a plateau, extending the no-feedback period beyond this point may add little information while increasing assessment time. This issue may be particularly relevant for older adults, who may require more repeated trials to obtain reliable UFD estimates [9]. Shortening individual trials could therefore make UFD assessment more practical and, following independent validation, facilitate the future use of UFD assessment in clinical populations. Therefore, the third research question was whether force loss differed between the early and late phases of the no-feedback period and whether this difference was related to age. It was hypothesized that most force loss would occur during the early phase, with a small additional decline after stabilization.

2. Materials and Methods

2.1. Study Design and Participants

The present study was a secondary analysis of data collected from 24 healthy adults in a previously published investigation of UFD measurement reliability [9]. The present analyses

examined associations of age with UFD magnitude and temporal dynamics; these associations were not examined in the previous report. Participants were recruited through an open invitation. The sample comprised 13 women and 11 men aged 18–69 years (mean ± SD age: 36.0 ± 19.0 years), with a mean height of 173.1 ± 10.4 cm and body mass of 70.5 ± 9.3 kg. The distribution of individual participant ages across the observed age range is illustrated in Figure 3. No participant reported a neurological disorder or current injury affecting the upper extremities. All participants reported being right-handed. To be eligible, individuals had to report engaging in less than 6 h of planned exercise per week and no regular participation in organized sport. Weekly exercise frequency and duration were assessed by self-report during the eligibility interview. All participants provided written informed consent. The study protocol was approved by the Institutional Review Board (No. 4-VII/2024), and all procedures were conducted in accordance with the Declaration of Helsinki.

2.2. Equipment

Force from each arm was measured separately by a uniaxial load cell (model 060-P665-01, Honeywell Sensotec, Columbus, OH, USA) incorporated into a custom-built dynamometer. The two force channels were acquired simultaneously at 1500 Hz with a DTS Desktop system and MyoResearch software (ver. 3.20.68, Noraxon Inc., Scottsdale, AZ, USA). During visual feedback, a computer monitor showed the combined force produced by both arms in real time.

2.3. Experimental Procedure

Participants performed bilateral isometric elbow flexion while seated at the dynamometer (Figure 1). Their chest rested against a Scott bench pad, and both arms were supported. The seat height, spacing between the dynamometer arms, and distance from the bench were adjusted for each participant to provide a comfortable and consistent, standard elbow position. Handles were secured around the forearms immediately above the wrists. A monitor was placed at eye level approximately 1 m in front of the participant and displayed the target force and, when available, the force produced by both arms. After a brief familiarization with the apparatus and visual feedback, participants performed three maximal voluntary contractions (MVC) during bilateral isometric elbow flexion. Each of them lasted 3 s with 30 s of rest period between them; standardized verbal encouragement was provided during each effort. The highest combined force recorded across the three contractions was defined as bilateral MVC. The target for the subsequent task was 20% MVC, with 19–21% MVC designated as the acceptable target range.

In the main task, participants completed six consecutive trials in each of two conditions (with and without feedback: Feedback ON, Feedback OFF). The order of the conditions was randomized. Each 35 s trial comprised a 5 s ramp-up phase, a 20 s force-maintenance phase, and a 10 s rest period. Participants were instructed to reach the target as quickly as possible during the first 5 s and then maintain that force for the following 20 s. Auditory cues marked the beginning and end of force production time. In the Feedback ON condition, visual feedback of the combined force remained available throughout all force production phases. In the Feedback OFF condition, visual feedback was removed at 5 s, while participants continued to maintain the intended force for the next 20 s. Feedback was restored during the rest period after force had returned to zero. The two conditions were separated by at least 3 min of rest.

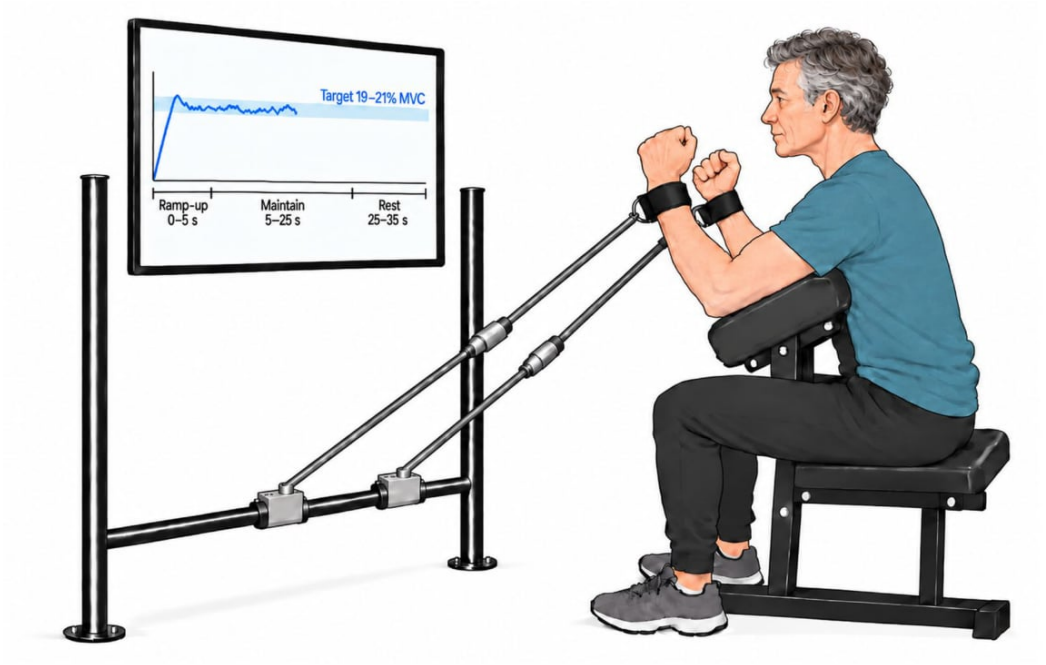

Figure 1. Experimental setup and trial structure. Participants performed bilateral isometric elbow flexion while seated with the chest and forearms supported. Force from each arm was measured separately, and the monitor displayed the target range (19–21% MVC) and combined force when visual feedback was available. Each trial comprised a ramp-up period (0–5 s), force maintenance (5–25 s), and rest (25–35 s). In the Feedback OFF condition, visual force feedback was removed at 5 s. The phase labels and timeline are included for illustration only and were not shown to participants.

2.4. Data Processing

Force data were processed offline using MATLAB R2025b (MathWorks, Natick, MA, USA). The signal from each load cell was low-pass filtered with a fourth-order, zero-phase Butterworth filter at 10 Hz. The filtered signals were then summed to obtain bilateral force, which was expressed as a percentage of the bilateral MVC determined during testing (%MVC). Force drift was quantified from mean bilateral force in two 500 ms windows within each trial: (t_1): 4.5–5.0 s and (t_2): 24.0–24.5 s (Figure 2) [8–10]. The t_1 window ended when visual force feedback was removed in the Feedback OFF condition (at 5 s); the second preceded the auditory cue to stop producing force. For each trial, drift was calculated as:

$$\text{Force Drift} = ((F(t_2) - F(t_1))/F(t_1)) \times 100 \quad (1)$$

where $F(t_1)$ and $F(t_2)$ denote mean bilateral force within the respective windows. Trial values were averaged across the six trials to obtain one estimate for each participant in each feedback condition. Negative values indicated a decline in force between t_1 and t_2.

To examine how force changed over time in relation to age, the six Feedback OFF force trials were averaged separately for each participant. Mean force was calculated for the 4.5–5.0 s interval, immediately before removing visual feedback and for each of the next 20 consecutive 1 s time intervals from 5 to 25 s, consistent with previous analyses of force trajectories using 1 s time bins [3,16,17]. The t_1 value was used as a reference whereas the 20 values obtained after feedback removal were used to analyze changes in force over time. In addition, for each participant, the difference between the two overall force drift values was calculated as Feedback OFF minus Feedback ON.

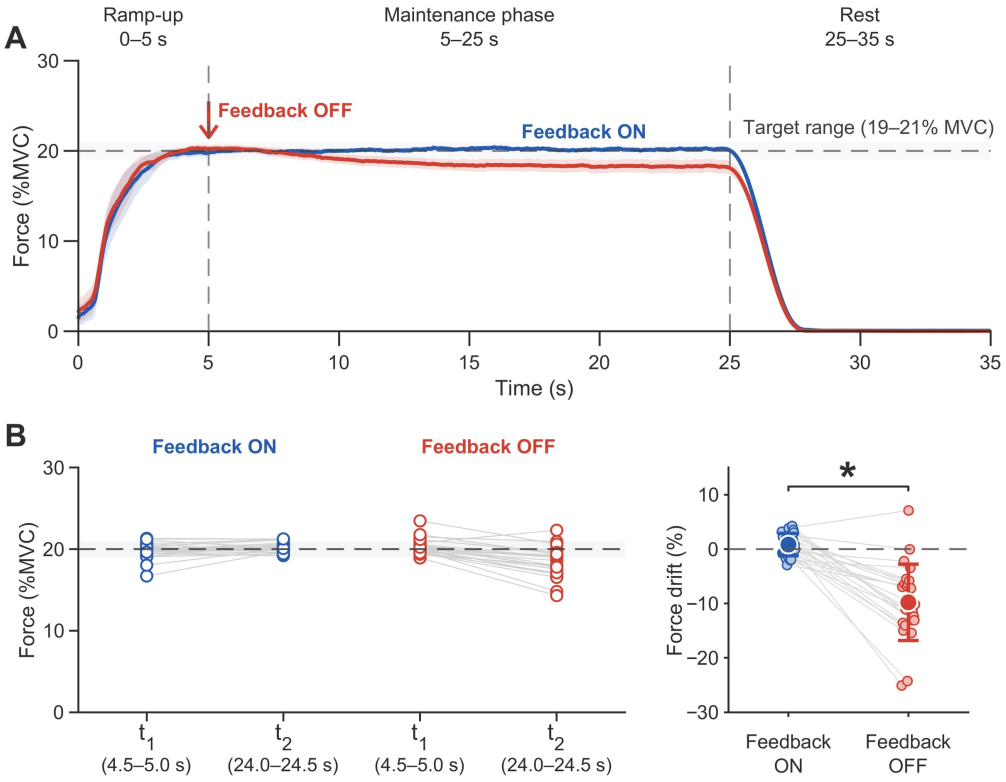

Figure 2. Visual feedback removal induces unintentional force drift. (**A**) Mean force trajectories during the task. Visual feedback was maintained in the Feedback ON condition (blue) and removed at 5 s in the Feedback OFF condition (red). The shaded horizontal area indicates the target force range of 19–21% MVC. (**B**) Force measured at t_1 and t_2 (**left**) and the resulting force drift (**right**). Open circles represent individual participants, grey lines connect paired observations, and filled circles with error bars represent the mean ± SD (* $p < 0.001$).

To examine the temporal dynamics of force drift after visual feedback removal, the 20 previously defined 1 s time intervals were used. For each participant, force change relative to t_1 was calculated for every interval in each trial, separately for the Feedback ON and Feedback OFF conditions. The force changes were then averaged across the six trials within each condition.

To quantify the additional force loss associated with visual feedback removal, the difference in force change between conditions was calculated at each interval as Feedback ON minus Feedback OFF, with positive values indicating greater force loss in the Feedback OFF condition. Furthermore, to assess how rapidly force loss developed, its discrete first derivative was calculated for each participant as the change from one 1 s interval to the next.

Next, an exploratory analysis examined when force loss began and reached a plateau. Force-loss values were averaged across participants at each of the 20 intervals to obtain a group trajectory. After the plateau was identified, a participant-level analysis examined whether shorter measurement durations produced results similar to the 20 s measurement. Using data from the same 20 s trials, force loss was recalculated for durations of 5–19 s using 500 ms windows ending 0.5 s before each endpoint, as in the 20 s calculation. For each participant, signed and absolute differences between each shorter-duration result and the 20 s result were calculated.

Finally, to examine whether the relationship between age and force drift differed over time, the 20 s period after feedback removal was divided into an early period (0–10 s) and a late period (10–20 s). For each participant and feedback condition, mean force was

calculated in three 500 ms windows: (t_1): 4.5–5.0 s, (t_{middle}): 14.0–14.5 s and (t_2): 24.0–24.5 s. Early force drift was calculated as:

$$\text{Early Force Drift} = ((F(t_{middle}) - F(t_1))/F(t_1)) \times 100 \quad (2)$$

and late force drift as:

$$\text{Late Force Drift} = ((F(t_2) - F(t_{middle}))/F(t_1)) \times 100 \quad (3)$$

where both drift values were expressed relative to the initial force level at t_1. For each participant, the difference between feedback conditions was calculated separately for the early and late periods as Feedback ON drift minus Feedback OFF drift. The within-participant difference between periods was then calculated as early loss minus late loss.

2.5. Statistical Analysis

Statistical analyses were performed using Statistica 13 (TIBCO Inc., Palo Alto, CA, USA). Descriptive results are reported as means and standard deviations (SD), with 95% confidence intervals (CIs) where indicated. Repeated-measures analysis of covariance (rmANCOVA) was used to analyze force measurements over time, with age entered as a continuous variable. For within-participant factors with more than two levels, sphericity was assessed using Mauchly's test, and the Greenhouse–Geisser correction was applied when the assumption was violated. Overall force drift was compared between Feedback ON and Feedback OFF using a paired-samples *t*-test. Effect sizes were reported as Cohen's (d_z for the *t*-test and partial eta squared (η_p^2) for rmANCOVA. Statistical significance was set at $p < 0.05$).

To assess whether changes in force, after visual feedback removal, were related to age, the 20 Feedback OFF force values for each participant were analyzed using rmANCOVA, with time as a within-participant factor and age as a continuous variable. The time–age interaction tested whether force trajectories varied with age. Individual trajectories were presented descriptively. Model estimated trajectories at 25, 45, and 65 years were used to illustrate the results, while age remained continuous in the analysis. Associations between age and overall force drift were examined using separate linear regressions for the Feedback ON and Feedback OFF conditions. To compare the age slopes between conditions, each participant's difference in overall force drift, calculated as Feedback OFF minus Feedback ON, was regressed on age. Slopes and their $CI_{95\%}$ were expressed per 10-year increase in age.

The temporal dynamics of additional force loss were analyzed using rmANCOVA, with time as a within-participant factor and age as a continuous variable. The model tested the effects of time, age, and their interaction. Model estimated trajectories at 25, 45, and 65 years were used to illustrate the results, while age remained a continuous variable in the analysis. To examine the rate of force loss, the 19 discrete first derivative values were analyzed using a separate rmANCOVA with the similar model structure. This model tested whether the rate changed over time and whether its temporal pattern varied with age. To estimate the onset and plateau of force loss, two three-parameter models were fitted to the single group-average trajectory obtained by averaging force-loss values across all 24 participants at each of the 20 one-second intervals: a delayed exponential model and a linear-to-plateau model. The delayed exponential model was defined as:

$$L(t) = A\,[1 - \exp(-\max(t - t_0,0)/\tau)], \quad (4)$$

and the linear-to-plateau model as:

$$L(t) = A\backslash\min[\max((t - t_0)/(t_p - t_0),0),1], \quad (5)$$

where (L(t)) represents the group-average additional force loss at time (t), (A) is the final force-loss amplitude, and (t_0) is the estimated onset time. The parameter (τ) is the time constant of the exponential model, and (t_p) is the plateau time of the linear-to-plateau model. Their relative fit was compared using the corrected Akaike information criterion (AICc) [18]. To evaluate shorter measurement durations, each participant's results obtained after 5–19 s were compared with their corresponding 20 s result. At each duration, the signed and absolute differences were averaged across participants and reported with 95% CIs.

Finally, the analysis examined whether the relationship between age and force drift differed between the early and late periods of the force maintenance phase. Each participant therefore contributed four drift values: Feedback ON and Feedback OFF drift for both the early and late periods. These values were analyzed using rmANCOVA, with feedback condition and period as within-participant factors and age as a continuous variable. The feedback-period-age interaction tested whether the difference between feedback conditions changed from the early to the late period as a function of age. To describe this interaction, force drift was regressed on age separately for each combination of feedback condition and period. Age was defined at the sample mean of 36 years and scaled in 10-year units, so that intercepts represented estimated drift at age 36 and slopes represented change per 10-year increase in age. The Feedback ON minus Feedback OFF contrast was then regressed on age separately for the early and late periods. Finally, the within-participant difference between these contrasts, calculated as early minus late, was regressed on age. The slope of this final regression corresponded to the feedback-period-age interaction in the rmANCOVA. All regression estimates were reported with 95% CIs.

3. Results

Following the removal of visual feedback, force output gradually declined across participants, confirming the presence of unintentional force drift (Figure 2A). To quantify this phenomenon, force drift was calculated separately for the Feedback ON and Feedback OFF conditions. Force drift was significantly larger ($t_{(23)} = -7.16$, $p < 0.001$, $d_z = 1.46$) in the Feedback OFF condition (mean ± SD: −9.78 ± 7.02%) than in the Feedback ON condition (0.83 ± 2.06%) (Figure 2B).

3.1. Force Drift in Relation to Age

Force output changed over time during the no-feedback condition (Figure 3A). The rmANCOVA showed a significant effect of time ($F_{(2.03,44.70)} = 31.40$, $p < 0.001$, $\eta_p^2 = 0.588$). Bonferroni-adjusted comparisons showed no significant changes during the first 3 s. Force then decreased significantly between 3 and 7 s, with no further significant changes after 7 s across participants. This pattern suggests that force stabilized during the later part of the task. Neither the effect of age ($F_{(1,22)} = 1.23$, $p = 0.279$, $\eta_p^2 = 0.053$) nor the age–time interaction ($F_{(2.03,44.70)} = 0.87$, $p = 0.428$, $\eta_p^2 = 0.038$) was significant. Furthermore, force trajectories were estimated at three representative ages within the observed age range. All three trajectories showed a similar decline followed by relative stabilization (Figure 3B). This pattern was consistent with the post hoc comparisons, which showed significant changes between 3 and 7 s but no further changes after 7 s.

In the next step, the relationship between age and force drift was examined independently for Feedback ON and Feedback OFF conditions (Figure 3C). No significant association was found in the Feedback ON condition (B = 0.39 percentage points per 10 years, $CI_{95\%}$ [−0.06, 0.84], $t_{(22)} = 1.81$, $p = 0.085$, $R^2 = 0.129$) or the Feedback OFF condition (B = 0.04 percentage points per 10 years, $CI_{95\%}$ [−1.59, 1.67], $t_{(22)} = 0.06$, $p = 0.956$, $R^2 < 0.001$). The condition specific regression slopes and their direct comparison are shown in Figure 3D. The difference between the slopes was not significant (B = −0.34 pp/10 years,

$CI_{95\%}$ [−2.02, 1.34], $t_{(22)} = -0.43$, $p = 0.675$, $R^2 = 0.008$), indicating no evidence that the relationship between age and force drift differed between conditions. To provide a more complete descriptive overview, individual force drift values were also presented across three age groups (Figure 3E). A similar pattern was observed in all three groups, with force drift remaining close to zero in the Feedback ON condition and becoming larger in the Feedback OFF condition.

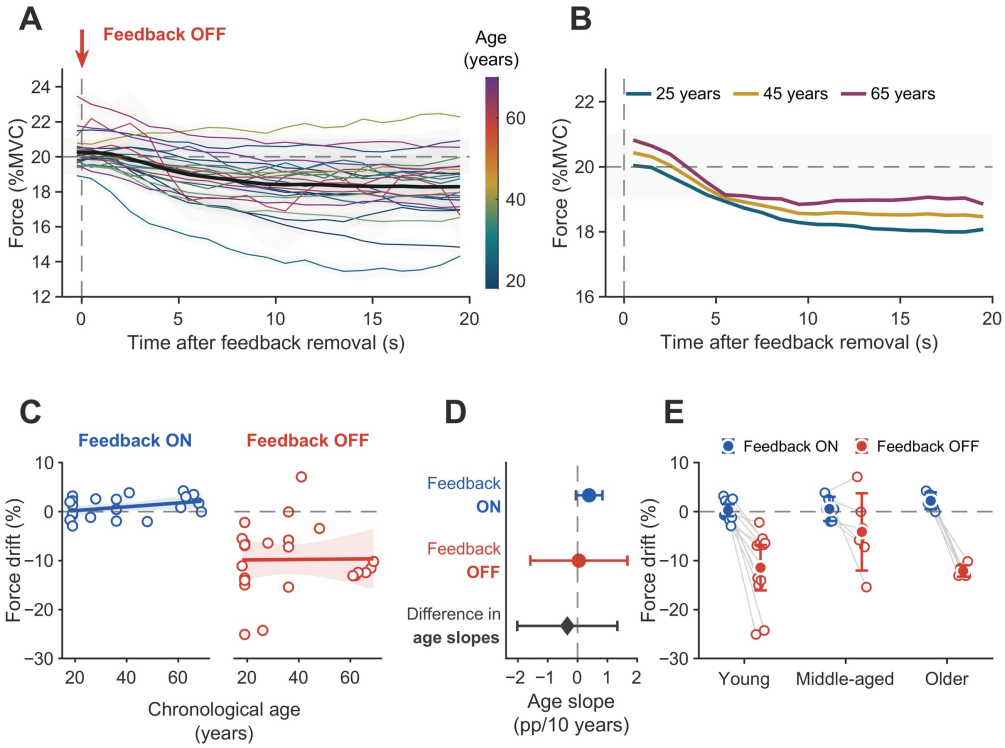

Figure 3. Force trajectories and the relationship between age and force drift. (**A**) Mean force trajectories for individual participants during the 20 s after visual feedback removal. Each coloured line shows one participant's mean trajectory across six trials. Line colour indicates participant age and the dark line shows the group mean. The grey area marks the target force range of 19–21% MVC. (**B**) Predicted force trajectories at ages 25, 45, and 65 years. Age was included as a continuous variable in the statistical model. (**C**) Relationships between age and force drift in the Feedback ON and Feedback OFF conditions. Open circles show individual participants, solid lines show the linear relationships and shaded areas show 95% CIs. (**D**) Age slopes for both conditions and their difference. Blue and red circles show the slopes for Feedback ON and Feedback OFF, respectively. The black diamond shows the difference between the slopes, and horizontal bars show 95% CIs. (**E**) Individual force-drift values for Feedback ON and Feedback OFF across three descriptive age groups. Open circles show individual values, grey lines connect paired observations, and filled circles with error bars show group means and 95% confidence intervals.

3.2. Temporal Dynamics of Force Drift

The force trajectories presented in Figure 3 suggested that force drift slowed and approached a relatively stable level following the initial decline. This apparent stabilization required a more detailed examination of its temporal dynamics. The difference in force loss between the Feedback ON and Feedback OFF conditions was therefore modelled across the 20 s interval (Figure 4A).

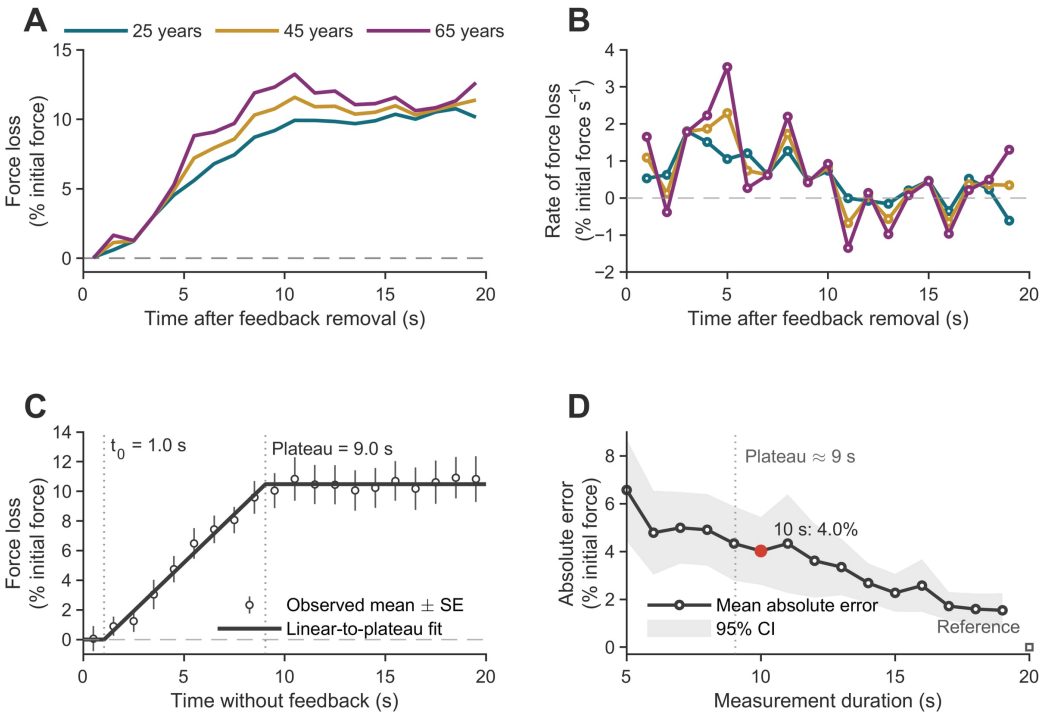

Figure 4. Temporal dynamics of force drift. (**A**) Modelled difference in force loss between the Feedback OFF and Feedback ON conditions over the 20 s interval. Lines show predictions for ages 25, 45 and 65 years. (**B**) Rate of change in force loss across consecutive 1 s intervals. The dashed line indicates zero change. (**C**) Group-average force loss (mean ± SE) and the linear-to-plateau fit. Dotted lines indicate the estimated onset (1.0 s) and plateau (9.0 s). (**D**) Mean absolute difference between endpoints obtained from shorter measurements and each participant's 20 s endpoint. The grey area shows the $CI_{95\%}$, the red point highlights the 10 s result, and the open square marks the 20 s reference. The dotted line marks the plateau estimated in panel (**C**). Age was analyzed as a continuous variable; 25, 45, and 65 years are model predictions, not separate groups (n = 24).

The predicted trajectories at 25, 45 and 65 years showed a similar pattern, with force loss increasing primarily during the first 10 s and showing only small changes during the remaining 10 s. The difference between the two feedback conditions increased significantly over time ($F_{(2.47, 54.26)} = 26.81$, $p < 0.001$, $\eta_p^2 = 0.55$). The association between age and the size of this difference was not statistically significant ($F_{(1, 22)} = 0.55$, $p = 0.465$, $\eta_p^2 = 0.025$). Its change over time was also unrelated to age ($F_{(2.47, 54.26)} = 0.55$, $p = 0.616$, $\eta_p^2 = 0.024$). Next, the rate of change was calculated across consecutive 1 s intervals to examine how quickly the difference between conditions developed (Figure 4B). The predicted rate profiles were similar at 25, 45, and 65 years. The largest positive rates occurred during the first half of the drift interval, whereas after approximately 10 s the rates fluctuated around zero. The rate of force loss varied significantly over time ($F_{(4.89, 107.48)} = 3.04$, $p = 0.014$, $\eta_p^2 = 0.12$). Neither the association with age ($F_{(1, 22)} = 0.51$, $p = 0.485$, $\eta_p^2 = 0.022$), nor the age–time interaction was statistically significant ($F_{(4.89, 107.48)} = 1.20$, $p = 0.315$, $\eta_p^2 = 0.052$). To further characterize the temporal dynamics of force drift, its onset and plateau times were estimated from the group-level trajectory (Figure 4C). A delayed exponential model was compared with a linear-to-plateau model. The delayed exponential model yielded an amplitude of 10.93% of the initial force, an onset time of 2.23 s, and a time constant of 3.53 s (($R^2 = 0.986$), AICc = −26.25). The linear-to-plateau model yielded an amplitude of 10.48% of the initial force, an onset time of 1.04 s, and a plateau time of 9.05 s (($R^2 = 0.991$), AICc = −35.63). The linear-to-plateau model was better supported than the delayed exponential model (ΔAICc = 9.38). Based on this model, the group-average force loss began approximately 1 s after feedback removal,

increased almost linearly, and reached a plateau at approximately 9 s. Based on this model, the group average force loss began after approximately 1 s and increased almost linearly until reaching a plateau at approximately 9 s. This group-level plateau led to a comparison of force-loss estimates from shorter measurements with the 20 s endpoint within each participant (Figure 4D). At 10 s, the group-average force loss was close to the 20 s endpoint (9.97% vs. 10.49% of the initial force), with a mean signed difference of −0.52 percentage points ($CI_{95\%}$: −2.75 to 1.71). However, the mean absolute error was 4.02 percentage points ($CI_{95\%}$: 2.61 to 5.44). This means that the 10 s estimates differed from the corresponding 20 s endpoints by approximately 4% of the initial force on average, regardless of the direction of the difference. As the measurement window was extended, the absolute difference between the shortened estimates and the corresponding 20 s endpoints generally decreased, reaching 1.54 percentage points at 19 s ($CI_{95\%}$: 0.83 to 2.25). Together, these findings suggested an exploratory division of the 20 s interval into an early period (0–10 s) and a late period (10–20 s). The next analysis examined whether the association between age and force drift differed between these two periods.

3.3. Early and Late Periods of Force Drift

The observed temporal dynamics led to a comparison of force drift in the early and late periods (Figure 5). Force trajectories from participants of different ages generally declined after feedback removal, and the mean trajectory began to stabilize around 10 s (Figure 5A). Despite variability among participants, the group-mean force trajectory remained nearly horizontal during the late period. Therefore, cumulative force drift showed a similar pattern: the mean force drop increased in the early period and appeared to stabilize in the late period (Figure 5B). At the mean age of 36 years, estimated force drift in the early period was 1.37% with Feedback ON and −9.01% with Feedback OFF. In the late period, the corresponding estimates were 0.04% and −0.53% (Figure 5C,D). The difference between feedback conditions was much greater in the early than in the late period (Period × Feedback: $F_{(1,22)} = 28.32$, $p < 0.001$, $\eta_p^2 = 0.563$). There was no evidence that the early–late difference varied with age, either overall (Period × Age: $F_{(1,22)} = 0.16$, $p = 0.697$, $\eta_p^2 = 0.007$) or between feedback conditions (Period × Feedback × Age: $F_{(1,22)} = 1.19$, $p = 0.287$, $\eta_p^2 = 0.051$). Furthermore, the feedback contrast described above was examined within each participant (Figure 5E). At the mean age of 36 years, additional force loss with feedback OFF was 10.38 percentage points in the early period and 0.57 percentage points in the late period. The paired early–late difference was 9.80 percentage points ($CI_{95\%}$ [5.98, 13.63]). This difference was then examined in relation to age. The estimated change in this early–late difference was 1.08 percentage points per 10 years of age ($CI_{95\%}$ [−0.97, 3.13]; Figure 5F). The size of this difference also varied among participants of similar ages. Finally, Figure 5G brings together the age slopes for each period and feedback condition, along with the slopes for their within-participant contrasts. Five of the seven age estimates lie to the right of zero (Figure 5G). In the drift rows, a point on the right indicates more positive drift with increasing age; in the contrast rows, it indicates a larger difference between the measures being compared. Taken together, these estimates did not indicate a substantial change in the relationship between age and force drift from the early to the late period.

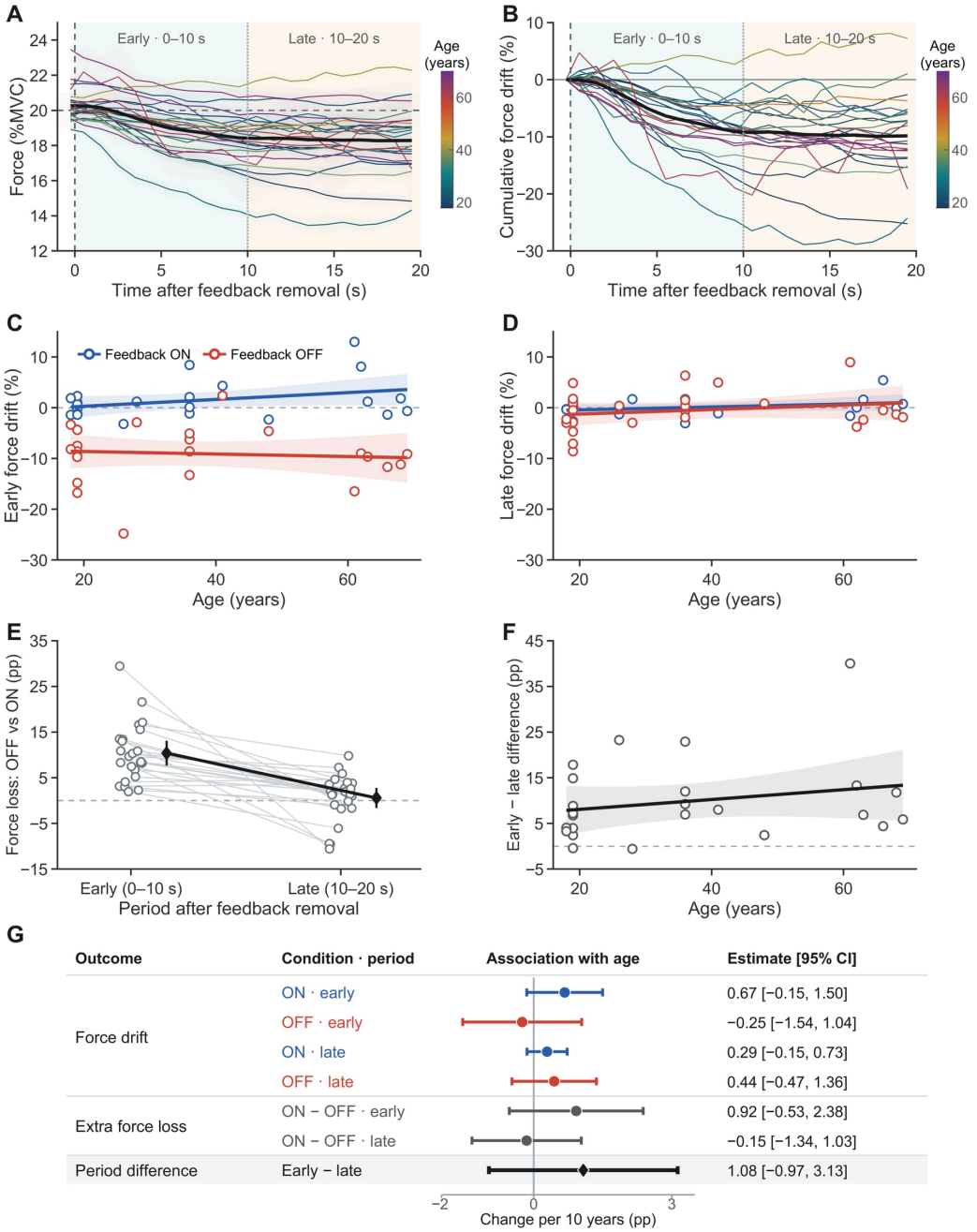

Figure 5. Early and late periods of force drift after feedback removal. (**A**) Force trajectories with feedback OFF for all 24 participants. Line colour indicates age; the dark line shows the participant mean. Background colours mark the early (0–10 s) and late (10–20 s) drift periods. (**B**) The same trajectories expressed as cumulative force drift relative to the mean force measured immediately before feedback removal (4.5–5.0 s). (**C**,**D**) Individual drift values and relationships with age for the early and late periods, respectively, under Feedback ON and OFF. Shaded areas represent 95% confidence intervals for means. (**E**) Force loss with Feedback OFF versus ON in each period. Thin lines connect each participant's values; diamonds and vertical lines show results at age 36 years and their 95% confidence intervals. (**F**) The difference between each participant's early and late force loss in relation to age. The line and shade area show the estimation and its 95% confidence interval. (**G**) Age slopes for the four drift periods outcomes and three within-participant contrasts. Circles show the estimated change per 10 years; horizontal lines show 95% confidence intervals. Negative drift indicates force loss.

4. Discussion

Force remained relatively stable while visual feedback was available but gradually declined after it was removed. Contrary to the age-related hypothesis, the associations of age with UFD magnitude and its time course were not statistically significant. The average force-loss trajectory began to decline approximately 1 s after feedback removal, changed almost linearly, and reached a plateau after approximately 9 s. At the group level, most force loss therefore occurred during the first 10 s, with little further change during the late period. The difference between the early and late periods was also unrelated to age. Finally, the similarity between the outcomes obtained after 10 and 20 s supports further investigation of shorter assessment durations as a possible way to simplify the protocol.

Force control often becomes less precise and more variable with age [1,2]. These age-related differences may reflect motor units remodelling, changes in neural drive, and altered sensory and visuomotor processing [1,19,20]. However, their magnitude may de-pend on different aspects such as the force level, availability of visual feedback, specific muscle group, and type of the motor task [15,19–22]. Based on that, UFD could be expected to become greater with age. Contrary to this expectation, the achieved outcomes did not support this hypothesis. Furthermore, UFD appeared to stabilize over time and its trajectory did not differ with age. To interpret these findings, force steadiness should be distinguished from UFD. Force steadiness reflects short-term fluctuations around a target [1,2,19–22], whereas UFD focus on gradual change in the force level after visual feedback is removed [3–5]. Therefore, greater force variability with age [20,23,24] does not necessarily imply a larger or faster UFD. This distinction is also consistent with the earlier reliability analysis, which showed lower UFD reproducibility and greater measurement error in older adults [9]. These findings suggest that ageing may increase variation across repeated UFD measurements without systematically changing the average value of drift. One possible straightforward explanation for this pattern is that force control changes after visual feedback is removed. Rapid visuomotor corrections are often altered with age [19,20], and age-related differences in bimanual force control have been reported in the presence, but not in the absence, of visual feedback [25]. Another explanation concerns the level at which force is controlled. Age-related reductions in force steadiness are linked to rapid changes in motor-unit activity and neural drive [1,23,24]. In contrast, UFD may reflect a slower change in the force control at the task level [3–5]. This distinction may be important in the bilateral task, where the main outcome was the combined force produced by both arms. Changes in one arm could have been partly balanced by changes in the other, reducing age-related differences in the combined force [22,26]. However, coordination between the arms was not examined directly, so this explanation remains only speculative. Another explanation concerns the force level used in the task. Although maximal muscle strength generally declines with age [27], the target was set at 20% of each participant's MVC. Participants therefore performed the task at the same relative force level despite differences in absolute strength. The short duration and low relative intensity of the task also limited the likely influence of fatigue. Each contraction was maintained for only 20 s, whereas fatiguing isometric contractions of the elbow flexors at 20% MVC can be sustained for several minutes [28]. Although fatigue was not measured directly, a previous analysis of these data found no systematic changes in mean force or force drift across the six trials [9]. Together, these features may have reduced age-related differences in task demands and may help explain why UFD did not increase with age as hypothesized.

Beyond its overall magnitude, UFD followed a clear temporal pattern rather than progressing at a constant rate throughout the task. After a brief delay following visual feedback removal, force declined at a nearly constant rate before reaching a relatively stable level. Previous studies have similarly shown that force loss may slow over time and approach

a stable level [6,29]. A more complex time course has been observed in force-matching tasks, where force drift may initially accelerate before slowing, stabilizing, or even reversing [8,11]. Despite differences between tasks, these studies show that both the rate and direction of force drift may change over time. One explanation for this changing time course is offered by referent-coordinate theory. According to this theory, force is produced by setting an intended limb configuration that differs from its actual position [4–6,29,30]. As the referent configuration gradually shifts toward the actual position, the difference between them becomes smaller, which may reduce muscle activation and force [6,29]. The plateau may therefore indicate that the system reached a new, unintended lower-force level. Overall, UFD may represent a gradual transition to a new force-control state rather than a continuous loss of force.

The gradual development of UFD raises an important methodological question about when force loss should be assessed after visual feedback removal [6,8,29]. In the Feedback OFF condition, participants reached the target during a 5 s period with visual feedback and then attempted to maintain the same force for 20 s without feedback. Although all participants completed the procedure, repeating sustained contractions may increase the assessment difficulty for individuals with reduced physical capacity. This issue may be particularly relevant to some older adults and clinical populations, as fatigability varies widely depending on task demands and individual characteristics [31]. Whether a shorter no feedback period could reduce assessment demands without compromising measurement quality remains uncertain, particularly when several trials are required to obtain a reliable estimate [9]. In the present study, most force loss occurred early in the no feedback period, and the force loss estimate after 10 s was, on average, close to that obtained after 20 s. However, the agreement between the 10 s and 20 s estimates varied across participants. In addition, the plateau was identified from the group-averaged trajectory and cannot be assumed to reflect stabilization at the same time in every participant. These results support further evaluation of shorter trials but do not yet justify a recommendation to reduce the assessment duration.

Several features of the study provide important context for these results. First, the sample included twenty-four participants across a broad age range, with relatively few participants at the upper end of this range. The sample size may have influenced the precision of the age-related estimates, which should be considered when interpreting the estimates and their 95% confidence intervals. Further research with larger, clearly defined age groups could extend these findings by directly comparing younger and older adults rather than examining age only as a continuous variable. Second, the analysis focused on the total force produced by both arms. It could therefore not determine whether a change in one arm was partly affected by a change in the other. This possibility requires a separate analysis of interlimb coordination using the uncontrolled manifold framework [26]. Third, participants reached the target during the 5 s feedback period, but it is not known whether allowing more time for force stabilization would change the magnitude or time course of UFD. While these considerations identify directions for future research, the age-related and temporal analyses extend current knowledge of UFD and provide a basis for improving its assessment. In summary, the average UFD trajectory was characterized by an early force decline followed by relative stabilization, while neither its magnitude nor its temporal dynamics showed a significant association with age. Shorter trials could simplify UFD assessment, but their measurement reliability and individual level agreement with the 20 s protocol need to be independently validated before they can be recommended.

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References

1. Pethick, J.; Taylor, M.J.D.; Harridge, S.D.R. Aging and skeletal muscle force control: Current perspectives and future directions. *Scand. J. Med. Sci. Sports* **2022**, *32*, 1430–1443. [CrossRef]
2. Camacho-Villa, M.A.; Giráldez-García, M.A.; Sevilla-Sanchez, M.; Rivera-Mejía, S.L.; Carballeira, E. Relationship between force steadiness and functionality in older adults: A systematic review with meta-analysis. *Scand. J. Med. Sci. Sports* **2025**, *35*, e70040. [CrossRef]
3. Vaillancourt, D.E.; Russell, D.M. Temporal capacity of short-term visuomotor memory in continuous force production. *Exp. Brain Res.* **2002**, *145*, 275–285. [CrossRef]
4. Ambike, S.; Zatsiorsky, V.M.; Latash, M.L. Processes underlying unintentional finger-force changes in the absence of visual feedback. *Exp. Brain Res.* **2015**, *233*, 711–721. [CrossRef]
5. Latash, M.L. Production and perception of intentional and unintentional actions. *J. Hum. Kinet.* **2021**, *76*, 51–66. [CrossRef]
6. Solnik, S.; Qiao, M.; Latash, M.L. Effects of visual feedback and memory on unintentional drifts in performance during finger-pressing tasks. *Exp. Brain Res.* **2017**, *235*, 1149–1162. [CrossRef]
7. Rannama, I.; Zusa, A.; Latash, M.L. Unintentional force drifts in the lower extremities. *Exp. Brain Res.* **2023**, *241*, 1309–1318. [CrossRef]
8. Pawłowski, M.; Ricotta, J.M.; De, S.D.; Latash, M.L. Force matching: Motor effects that are not reported by the actor. *Exp. Brain Res.* **2024**, *242*, 1439–1453. [CrossRef]
9. Pawłowski, M. Measuring unintentional force drift: Reliability, number of trials, and age-related differences. *Sensors* **2026**, *26*, 5912. [CrossRef]
10. Abolins, V.; Latash, M.L. Unintentional force drifts as consequences of indirect force control with spatial referent coordinates. *Neuroscience* **2022**, *481*, 156–165. [CrossRef]
11. Rannama, I.; Zusa, A.; Latash, M.L. Force drifts and matching errors in the lower extremities: Implications for the control and perception of foot force. *Exp. Brain Res.* **2025**, *243*, 37. [CrossRef]
12. Slifkin, A.B.; Vaillancourt, D.E.; Newell, K.M. Intermittency in the control of continuous force production. *J. Neurophysiol.* **2000**, *84*, 1708–1718. [CrossRef]
13. Vieluf, S.; Sleimen-Malkoun, R.; Voelcker-Rehage, C.; Jirsa, V.; Reuter, E.-M.; Godde, B.; Temprado, J.-J.; Huys, R. Dynamical signatures of isometric force control as a function of age, expertise, and task constraints. *J. Neurophysiol.* **2017**, *118*, 176–186. [CrossRef]
14. Knol, H.; Huys, R.; Temprado, J.-J.; Sleimen-Malkoun, R. Performance, complexity and dynamics of force maintenance and modulation in young and older adults. *PLoS ONE* **2019**, *14*, e0225925. [CrossRef]
15. Hu, X.; Newell, K.M. Aging, visual information, and adaptation to task asymmetry in bimanual force coordination. *J. Appl. Physiol.* **2011**, *111*, 1671–1680. [CrossRef]
16. Vaillancourt, D.E.; Slifkin, A.B.; Newell, K.M. Visual control of isometric force in Parkinson's disease. *Neuropsychologia* **2001**, *39*, 1410–1418. [CrossRef]
17. Neely, K.A.; Mohanty, S.; Schmitt, L.M.; Wang, Z.; Sweeney, J.A.; Mosconi, M.W. Motor memory deficits contribute to motor impairments in autism spectrum disorder. *J. Autism Dev. Disord.* **2019**, *49*, 2675–2684. [CrossRef]
18. Hurvich, C.M.; Tsai, C.-L. Regression and time series model selection in small samples. *Biometrika* **1989**, *76*, 297–307. [CrossRef]
19. Tracy, B.L.; Dinenno, D.V.; Jorgensen, B.; Welsh, S.J. Aging, visuomotor correction, and force fluctuations in large muscles. *Med. Sci. Sports Exerc.* **2007**, *39*, 469–479. [CrossRef]

20. Tracy, B.L.; Hitchcock, L.N.; Welsh, S.J.; Paxton, R.J.; Feldman-Kothe, C.E. Visuomotor correction is a robust contributor to force variability during index finger abduction by older adults. *Front. Aging Neurosci.* **2015**, *7*, 229. [CrossRef]
21. Vieluf, S.; Temprado, J.J.; Berton, E.; Jirsa, V.K.; Sleimen-Malkoun, R. Effects of task and age on the magnitude and structure of force fluctuations: Insights into underlying neuro-behavioral processes. *BMC Neurosci.* **2015**, *16*, 12. [CrossRef]
22. Rudisch, J.; Müller, K.; Kutz, D.F.; Brich, L.; Sleimen-Malkoun, R.; Voelcker-Rehage, C. How age, cognitive function and gender affect bimanual force control. *Front. Physiol.* **2020**, *11*, 245. [CrossRef]
23. Tracy, B.L.; Enoka, R.M. Older adults are less steady during submaximal isometric contractions with the knee extensor muscles. *J. Appl. Physiol.* **2002**, *92*, 1004–1012. [CrossRef]
24. Galganski, M.E.; Fuglevand, A.J.; Enoka, R.M. Reduced control of motor output in a human hand muscle of elderly subjects during submaximal contractions. *J. Neurophysiol.* **1993**, *69*, 2108–2115. [CrossRef]
25. Critchley, K.; Kokubu, M.; Iemitsu, M.; Fujita, S.; Isaka, T. Age-related differences in the availability of visual feedback during bimanual pinch. *Eur. J. Appl. Physiol.* **2014**, *114*, 1925–1932. [CrossRef]
26. Reschechtko, S.; Latash, M.L. Stability of hand force production. II. Ascending and descending synergies. *J. Neurophysiol.* **2018**, *120*, 1045–1060. [CrossRef]
27. Mitchell, W.K.; Williams, J.; Atherton, P.; Larvin, M.; Lund, J.; Narici, M. Sarcopenia, dynapenia, and the impact of advancing age on human skeletal muscle size and strength: A quantitative review. *Front. Physiol.* **2012**, *3*, 260. [CrossRef]
28. Yoon, T.; Schlinder-Delap, B.; Hunter, S.K. Fatigability and recovery of arm muscles with advanced age for dynamic and isometric contractions. *Exp. Gerontol.* **2013**, *48*, 259–268. [CrossRef]
29. Ambike, S.; Mattos, D.; Zatsiorsky, V.M.; Latash, M.L. Unsteady steady-states: Central causes of unintentional force drift. *Exp. Brain Res.* **2016**, *234*, 3597–3611. [CrossRef]
30. Latash, M.L. Motor synergies and the equilibrium-point hypothesis. *Mot. Control* **2010**, *14*, 294–322. [CrossRef]
31. Hunter, S.K. Performance fatigability: Mechanisms and task specificity. *Cold Spring Harb. Perspect. Med.* **2018**, *8*, a029728. [CrossRef]

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