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RESEARCH ARTICLE

Slowing of dexterous manipulation in old age: force and kinematic findings from the 'nut-and-rod' task

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Abstract The task of sliding a nut from a rod has been used to study manual slowing in old age (Smith et al. in Neurology 53:1458–1461, 1999; Neurobiol Aging 26:883–890, 2005). In this experiment, we sought to determine if the age-related slowing in this task occurs with losses of motor precision, as indicated by the forces exerted on the rod. The forces exerted by the nut on the rod were monitored along with the kinematics of the hand in old and young adults while they attempted to lift a nut from three vertically oriented rods of different shape (straight, single curve, double curve). Old adults performed the task 64% slower than young adults for the straight rod, 100% slower for the single-curve rod, and 80% slower for the double-curve rod. Old adults did not differ from the young adults in the amount of force exerted against the rods in the horizontal plane, or in the steadiness of these forces, but exerted greater force impulses in the vertical direction over the course of a trial (359% straight, 236% single curve, 214% double curve) and much more force in the vertical direction (255% straight, 267% single curve, 159% double curve). Old adults also performed the task with 35% greater average roll of the hand into pronation. We suspect that old adults tilted the nut, even for the straight rod, dragging it against the rod to create the elevated vertical forces. These observations support previous speculation that old adults do not control the external moments applied to grasped objects as well as young adults.

Keywords Hand · Prehension · Slowing · Old age · Force · Grasp

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Introduction

Reports of declining manual dexterity in old age often focus on the ubiquitous finding of increased time to perform manual tasks (e.g., Welford 1958; Jebsen et al. 1969; Welford et al. 1969; Kellor et al. 1971). Advancing age particularly affects *dexterous* manipulation with the hand and digits (Desrosiers et al. 1999; Smith et al. 1999, 2005). Smith et al. (1999) studied the effects of age on the time needed to remove a nut from various shaped smooth rods (straight, single curve, and double curve). They reported a slight linear increase across the adult age span in the time required to lift the nut from a platform with no rod, whereas the time to remove the nut from a rod with a double curve showed a precipitous increase beginning around age 60 years. In a subsequent study of 497 cognitively and neurologically normal adults from 18 to 95 years of age, Smith et al. (2005) again demonstrated that the performance time for the double-curve rod underwent a marked increase in rate of slowing around age 62 years. Their analyses revealed a 12 ms/year rate of slowing for individuals between 30 and 62 years of age, and a 60 ms/year rate of slowing for individuals older than 62 years of age. Likewise, a rare longitudinal study of manual skills in healthy old age revealed slowing with increased age, and this slowing was greatest for precision manual tasks (Desrosiers et al. 1999).

Here we re-examine the task of sliding a nut over smooth rods of different shapes to determine if old adults show reduced precision in positioning and/or orienting the nut in relation to the rod. Precision was assessed indirectly by monitoring the forces exerted on the nut when in contact with the rods (Darling et al. 2006). High forces would indicate poor manipulation skills, for example when orienting the nut to negotiate curves in the rod. Reduced precision in positioning and orienting the nut are expected given reports of declining ability to produce smooth forces in hand muscles (Enoka et al. 2003), control the magnitude and direction of fingertip forces (Cole 1991, 2006; Cole et al. 1999), control the external moments applied to grasped objects (Shim et al. 2004; Olafsdottir et al. 2007), and a declining tactile sensory capacity that correlates with the increased time to manipulate objects in precision grip (Tremblay et al. 2003). We also were interested in how the instructed movement speed in this task affects the phenomenon of behavioral slowing, and motor precision. The age-related slowing in this task, and particularly the disproportionate slowing that has been reported for the curved rods, may reflect a compensatory strategy to avoid motor errors (loss of precision) that occurs mainly at faster performance speeds. Smaller forces at slower, more comfortable speeds would support this interpretation. We addressed this by instructing subjects to perform the tasks at a self-selected 'comfortable' speed in addition to performing the tasks 'as quickly as possible'.

Materials and methods

Eighteen healthy, community-dwelling adults participated in the experiments (five females and five males 21–22 years of age; seven females and one male 65–83 years of age with an average age of 74 years). All subjects were free from neurological disease or injury, or diseases of the hand. They were screened via a questionnaire for a history of disease or injury that may affect control of the upper extremities. This screening instrument included items about: (1) central or peripheral nervous system injury or disease such as stroke, Parkinson's disease, trauma, (2) surgery of the hand or arm, (3) injury or disease affecting the nerves supplying the arms and hands, (4) pain requiring daily medication, (5) high blood pressure requiring medication, (6) diabetes, and (7) arthritis requiring medication. They correctly answered simple questions designed to screen for impaired awareness of their surroundings and current events. They passed screening questions for carpal tunnel syndrome, which included questions about hand numbness and/or paresthesia, especially at night, and wrist pain. They demonstrated normal-for-age Semmes–Weinstein filament thresholds on the index finger of their dominant hand. These were obtained by presenting filaments to the pulp of the thumb of the subject, beginning with suprathreshold diameters and proceeding in descending fashion. Filaments were applied with a gentle application to obtain the needed filament buckling, rather than tapping or bouncing the filament. The threshold was taken to be the smallest diameter that could be detected upon 70% of applications. For the Young group, the tactile sensibility thresholds were 2.36–2.83 (mean 2.45). For the Old group the tactile sensibility thresholds were 2.44–3.22 (2.93). Although we did not ask the subjects in the Old group about their occupation, this group included several who commented about knitting and playing musical instruments as regular hobbies.

We used a task similar to that described by Smith et al. (1999, 2005) but modified to use a three-axis force/torque transducer (Nano 17, ATI, North Carolina) mounted on a table as the base into which straight and curved metal rods were attached (Fig. 1). This allowed us to monitor the forces applied to the rod along perpendicular axes in the horizontal plane (X, Y), and along the vertical axis (Z) and removed the restrictions on hand motion and orientation imposed by the chambers of the movement assessment panel that Smith et al. used. Forces were resolved to 0.003 N in each direction, according to the manufacturer's specification for the force/torque transducer system. The three rods (one straight, one with a single curve, and one with two curves) were made of hardened, polished steel with a diameter of 4 mm and were similar in length and shape to those used by Smith et al. (Fig. 1, inset). The nut that subjects were asked to slide over the rods had an outside diameter of 11 mm and a lumen diameter of 5 mm. Hand and forearm kinematics were monitored in three dimensions via electromagnetic sensors (miniBirds, Ascension Technologies, North Carolina) that were attached to the third metacarpal and the styloid process of the dominant (right) hand.

Subjects sat at a table in an adjustable chair at a comfortable distance from the apparatus. Each participant was instructed to rest their right arm on the table in front of them, with their thumb and index finger opened to enclose the nut. A 'comfortable' grasp aperture was selected by the subjects, with the instruction that they open their thumb and finger so that they were not touching the nut. Upon a verbal command from the experimenter they were to close their thumb and finger to grasp the nut, lift it completely clear of the rod, and then place the nut on a marked location and return their hand to the start position. The investigator returned the nut to the rod after each trial.

All subjects began with the straight rod and removed the nut five times at a self-selected 'comfortable' speed, followed by five repetitions to remove the nut 'as quickly as possible.' They were not allowed any additional trials prior to these for practice. This order was repeated for the double-curve rod, and then the single-curve rod. The instructions never addressed whether or not the nut should touch any of the rods, nor were there any instructions given on how to perform the task.

Data processing

Force data were sampled at a rate of 370 samples/s (Datapack 2K2 v3.10 RUN Technologies, Mission Viejo,

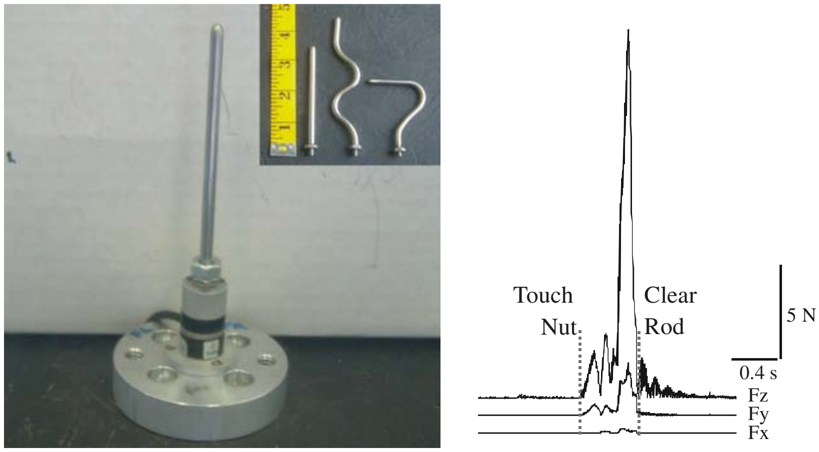

Fig. 1 Photograph of the nut and rod. At the base of the rod is the force/torque transducer. *Inset* shows the three rod shapes (straight, double curved, and single curve). The *right panel* shows an example of rectified horizontal (Fx, Fy) and vertical (Fz) forces recorded during a single trial performed by a subject in the Old group. The rise in Fz and Fy above background noise provided unambiguous indications of when the nut was touched (*left dotted vertical line*). The point at which the nut was assumed to clear the rod was indicated by the precipitous decrease in force, along with the appearance of oscillations consistent with the stiffness of the apparatus

California). Data were digitally filtered with a fifth order, zero-lag, low-pass 12 Hz Butterworth filter, and then rectified. Kinematic data were acquired at a rate of 74 samples/s (6-D Research v2.53, Skill Technologies, Phoenix, Arizona) then smoothed with a first order, zero-lag, low-pass 12 Hz Butterworth filter. Hand angles were computed as Cardan angles (ordered rotations about three orthogonal axes within the hand relative to the laboratory or earth-fixed coordinate system) of yaw (rotation about vertical axis), elevation (rotation about a medial–lateral or left–right axis) and roll (rotation about the longitudinal axis of the hand). Data from individual trials were up-sampled to a rate of 370 samples/s to allow kinematic data to be merged with force data.

Data analysis

For each trial we measured the time needed to remove the nut by determining when the nut was touched and when the nut cleared the rod. Initial contact with the nut caused force levels in one or more directions to change, but particularly in the vertical (Fz) direction because the nut rested on the force-torque transducer (Fig. 1). Contact with the nut was clearly indicated by the rise in Fz force above the small levels of background noise. The force levels showed fluctuations of varying magnitude continually during the task, typically in multiple directions, until the nut cleared the top of the rod. The point at which the nut was assumed to clear the rod was indicated by a precipitous decrease in force, along with the appearance of high frequency oscillations in the force signal. The complex oscillations always appeared at the end of a trial (although their amplitude varied across conditions and subjects), and matched the pattern of under-damped oscillation from lightly loading the top of the rod horizontally and then releasing it. These oscillations were considered an unambiguous marker for the moment the rod cleared the nut. The fact that they were always present may reflect the 1 mm clearance between the nut and rod, the instructed speeds, and no mention by the experimenters of attempting to avoid contact between the nut and rod. We are confident that, for either group, we did not underestimate the time between touching the nut and removing it from the rod.

The average force, and force impulse were measured in each direction over the duration of the trial after full-wave rectification around 0 N. The total impulse for each trial was calculated as the sum of the force impulses across the three force directions. The standard deviation of the force in each direction over the duration of each trial also was measured (before rectification) to provide an indication of force variability during the trial. We also measured the mean hand orientation (yaw, elevation and roll) and standard deviation of hand orientation for each trial.

For each of these measures, the mean value across the trials within a condition was obtained for each subject. The group means were entered into repeated-measures ANOVAs to determine the effects of Group (old, young), and within-subject factors of Rod Shape (straight, single curve, double curve), and Speed (comfortable, quick). The simultaneous within-subject hypotheses were treated as multivariate dependent variables, and the standard multivariate results were computed to avoid violations of sphericity and compound symmetry (STATISTICA version 7.1, StatSoft, Inc., Tulsa OK). Significance was set at $P < 0.05$. In no case did the statistical significance of the univariate analyses (with appropriate corrections; Greenhouse and Geisser

1958) differ from the multivariate analyses. Figures of scatter plots show group means under the 'quick' speed instruction, with whiskers indicating ±95% confidence intervals obtained from the statistical analyses.

Results

Subjects were not allowed to practice lifting the nut from the rod, so their first experience with the task for each rod occurred when they performed the five trials under the 'comfortable' speed instruction. These trials with each rod were examined to address potential learning effects. Indeed, both groups learned to perform the task quicker and with less rod contact across the five trials at the 'comfortable' speed for each rod. Performance did not show consistent improvements over five trials at quick speed. The duration and total force impulse for the first trial with each rod were compared to the average of trials four and five for the 'comfortable' and 'quick' blocks. The duration showed a main effect for Trial for the comfortable speed ($F_{1,16} = 60.37$; $P < 0.000001$) but not for the quick speed ($F_{1,16} = 0.5$; $P = 0.49$). In neither case was the Trial × Group interaction significant ($P = 0.59$ and 0.93 for comfortable and quick speeds, respectively). Likewise, total impulse showed a main effect for Trial for the comfortable speed ($F_{1,16} = 10.94$; $P < 0.004$) but not for the quick speed ($F_{1,16} = 2.29$; $P = 0.15$). In neither case was the Trial × Group interaction significant ($P = 0.18$ and 0.37 for comfortable and quick speeds, respectively). None of the Trial × Rod interactions were significant. In light of these findings, the reported results for the 'comfortable' speed task will reflect the average of trials four and five. These averages also were entered into the repeated-measures ANOVAs noted previously for the 'comfortable' level of the speed factor.

The time required for old and young subjects to remove the nut from the various rods (Fig. 2) replicated the findings of Smith et al. (1999). The Old group performed slower than the Young group across all conditions (main effect of Group; $F_{1,16} = 24.47$, $P < 0.0001$) and the curved rods yielded the longest durations for both groups (main effect of Rod Shape; $F_{2,15} = 113.1$, $P < 0.000001$). The Old group also showed disproportionately longer durations for the curved rods, and particularly for the single-curve rod (interaction of Group and Rod Shape; $F_{2,15} = 7.87$; $P < 0.004$).

The Old group exerted higher forces and impulses against the rod than the Young group (Figs. 2, 3). Analysis of the total force impulse (sum of the *horizontal* and *vertical* impulses) revealed that the Old group exerted more force than the Young group across all three rods (Fig. 2; main effect of Group; $F_{1,16} = 20.23$, $P < 0.0004$). The greatest forces for both groups were exerted while removing the nuts from the two curved rods (main effect of Rod; $F_{2,15} = 39.51$, $P < 0.00001$), with the Old group showing relatively greater increases in force for the curved rods (interaction of Rod and Group; $F_{2,15} = 5.35$, $P < 0.017$).

Most of the force exerted against the rods was in the vertical direction for the Old group (Fig. 2). The Old group produced force impulses in this direction that averaged

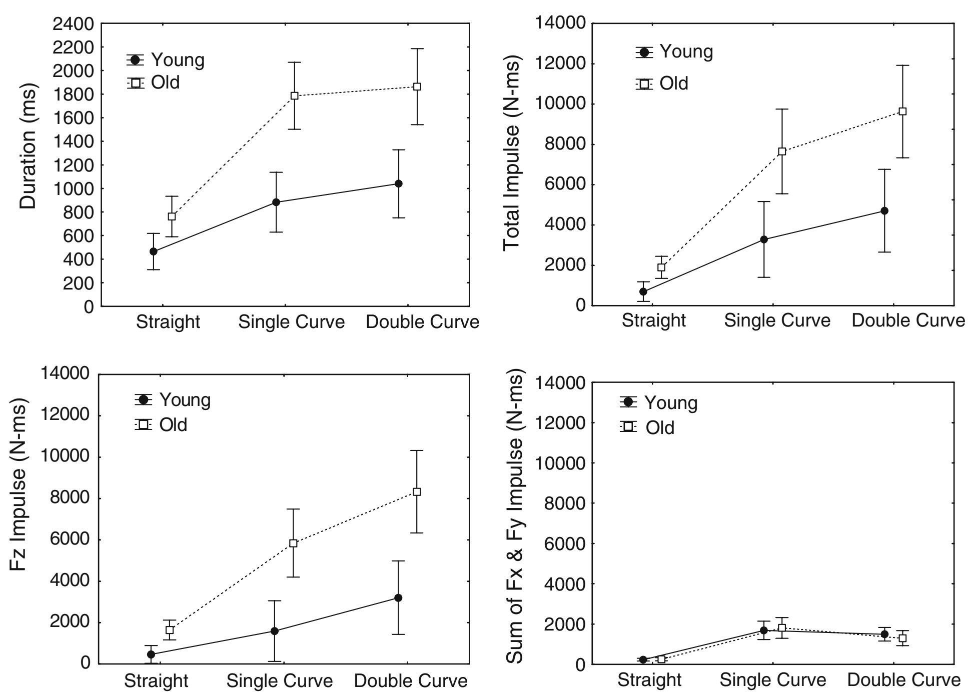

Fig. 2 Scatter plots (mean ±95% confidence interval). *Top right* average time needed to remove the nut from each rod for the Young group (*solid circles*) and the Old group (*open squares*). *Top left* average total impulse (sum of the horizontal and vertical force impulse) produced while removing the nut from each rod. *Bottom left* average vertical impulse. *Bottom right* average horizontal impulse (sum of Fx and Fy). Data shown from the 'quick' instruction blocks

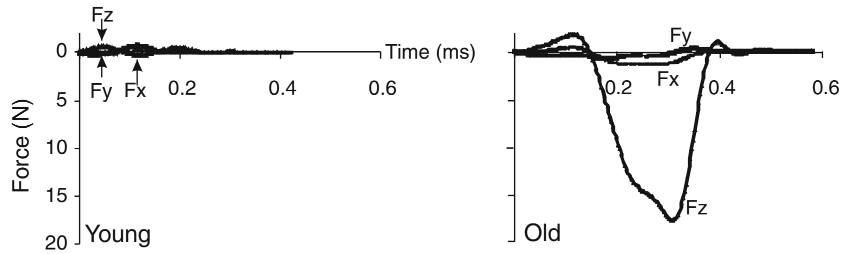

Fig. 3 Examples of *horizontal* (Fx, Fy) and *vertical* (Fz) forces exerted against the straight rod while a young (*left panel*) and old (*right panel*) subject removed the nut

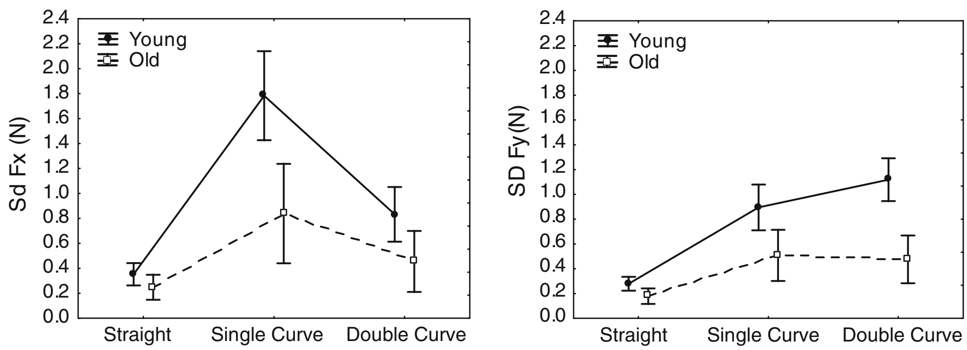

Fig. 4 Scatter plots of the average standard deviation of the horizontal forces (Fx *left*, Fy *right*) produced while removing the nut from each rod for the Young group (*solid circles*) and the Old group (*open squares*)

more than 3× larger than the Young group (main effect of Group; $F_{1,16} = 26.44$, $P < 0.0001$). By contrast, force impulses in the horizontal direction (sum of the impulses in the *X* and *Y* directions) were relatively small and did not differ across groups ($F_{1,16} = 0.04$, $P = 0.849$). The within-trial standard deviation of the horizontal force impulses did not differ between groups for the straight rod (Fig. 4). The young subjects demonstrated greater within-trial force variability than the old adults for the single and double-curved rods (interaction of Group and Rod for Fx; $F_{2,32} = 8.2$; $P < 0.001$ and for Fy; $F_{2,32} = 12.99$; $P < 0.0001$). For the Old group the vertical force impulse accounted for 86% of the total force impulse for the straight rod, 77% for the single-curve rod, and 87% for the double-curve rod. For the Young group the vertical force impulse accounted for 45, 40 and 62% of the total force across the straight, single-curve, and double-curve rods, respectively. The main effect of Group was significant for these percentages ($F_{1,16} = 56.6$, $P < 0.0001$).

The finding of high vertical forces for the Old group was a consistent finding across both male and female subjects (Fig. 5). All subjects in the Old group produced higher average vertical forces than nine of the ten subjects in the Young group. One subject in the Young group (a male) produced a higher average force and movement speed in the vertical direction than any of the subjects in the Old group. These data indicate that, among the young subjects, females showed no greater tendency towards producing high vertical forces against the rods than did young males.

The increased vertical force impulse in the Old group was explained only partially by their longer contact durations with the rods. The correlations between the size of the

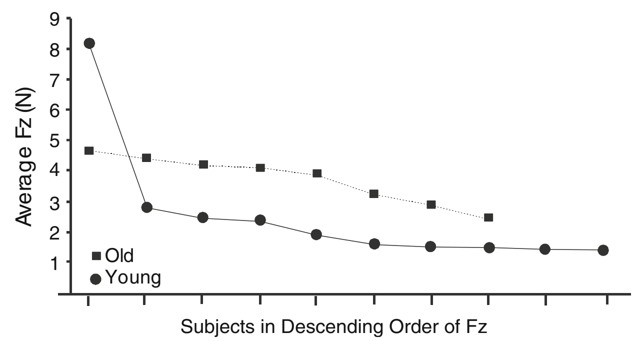

Fig. 5 Scatter plot of the average vertical force (Fz) for each subject, arranged from greatest to least force, for the Young (*solid*) and Old (*open*) subjects

vertical (Fz) impulse and the time taken to complete the task within the Old group yielded a single significant ($P < 0.05$) Pearson product-moment correlation ($r = 0.81$ for the single-curve rod, fast speed), although the remaining correlations for the Old group were from 0.36 to 0.67 (Table 1). There were no significant correlations for the Young group. Regardless of contact duration, the average vertical force (Fz) during a trial was greater for the Old Group (3.4 N) compared to the Young group (1.3 N) (main effect of Group; $F_{1,15} = 53.2$, $P < 0.00003$; Subject 1 in Fig. 5 eliminated as an outlier).

The old subjects' production of relatively large vertical force impulses against the straight rod is notable considering that the Old and Young groups produced force impulses of similar size in the horizontal plane. Analysis of hand 'roll' (measured at the hand dorsum) indicated that subjects in the Old group averaged 13° more roll in the pronation

Table 1 Pearson product-moment correlations between the average vertical (Fz) impulse and duration across subjects

Rod/speed	Young	Old
Straight/slow	0.25	0.36
Straight/fast	0.23	0.48
Single curve/slow	−0.10	0.58
Single curve/fast	−0.13	0.81*
Double curve/slow	0.03	0.67
Double curve/fast	−0.16	0.58

Correlations marked with asterisks indicate $P < 0.05$

direction compared to young adults for the straight rod, 22° more for the single-curve rod, but only 2° more for the double-curve rod (Fig. 6; interaction of Rod and Group; $F_{2,13} = 4.94$; $P < 0.025$). However, without measuring kinematics of the nut or the distal ends of the digits where the nut was grasped, we cannot confirm that this pronation tilted the nut. Despite showing greater hand roll, the Old group did not show greater within-trial variability of hand roll, except for the double-curved rod (interaction of Rod and Group; $F_{2,28} = 10.96$; $P < 0.0003$) .

Effects of instructed speed

The Old group continued to produce large force impulses even when performing at their self-selected 'comfortable' speed. Both groups took longer to perform the task under the 'comfortable' speed instruction (Young, 796 vs. 1,040 ms; Old, 1,470 ms vs. 1637 ms, for the 'quick' and 'comfortable' instructions, respectively). This was confirmed by a significant main effect of the 'Speed' factor ($F_{1,16} = 17.12$, $P < 0.0008$), and no significant interaction of the 'Speed' and 'Group' factors ($F_{1,16} = 0.59$, $P = 0.45$). The average duration decreased by 22% (Young) and 24% (Old) for the straight rod, and by 34% (Young) and 24% (Old) for the single-curve rod. Subjects were least able to increase their speed on the double-curve rod (12% for Young and 0% for Old), although there was no significant interaction of the 'Rod' and 'Group' factors ($P = 0.18$). At the slow speed the vertical force impulse averaged 1,270 N ms for the Young group, and 4,860 N ms for the Old group across all rods (main effect of Group as noted previously, and the absence of speed × group interaction; $F_{1,16} = 0.03$, $P = 0.86$). For the straight rod the vertical force impulse averaged 225 N ms for the Young group and 1,519 N ms for the Old group.

Discussion

Age-related manual slowing was substantial for the task of grasping a nut and sliding it from a metal rod, and worsened somewhat for the curved rods. These findings confirm those of Smith and colleagues despite our use of a slightly different task and a smaller nut (Smith et al. 1999, 2005). We agree with Desrosiers et al. (1999) conclusion that age-related behavioral slowing impacts dexterous manipulation more than simpler forms of grasp. We also agree that dexterous manipulation deteriorates even among healthy community-dwelling old adults.

The slowing persisted under instructions to perform the task at a self-selected 'comfortable' speed, although one cannot know how individual subjects interpreted such instructions in contrast to moving 'as quickly as possible'. However, it can be argued that slowing of movement under instructions to select a comfortable speed may better represent daily performance than under instructions to move "as quickly as possible." While analysis of the five trials at comfortable speed revealed reduced contact forces across trials one through five, we cannot determine whether the relatively large contact forces in the old adults that remained would have continued to fall with more practice. The forces did not fall for either group across the subsequent five trials at the fast speed, for any rod, but especially for the seemingly easiest task presented by the straight rod. For these reasons we suspect that the large contact forces for the old adults on the straight rod do not simply reflect unfamiliarity with the task or lack of practice. Moreover, the purpose of this work was not to address learning in young versus old in the novel, but relatively simple, task.

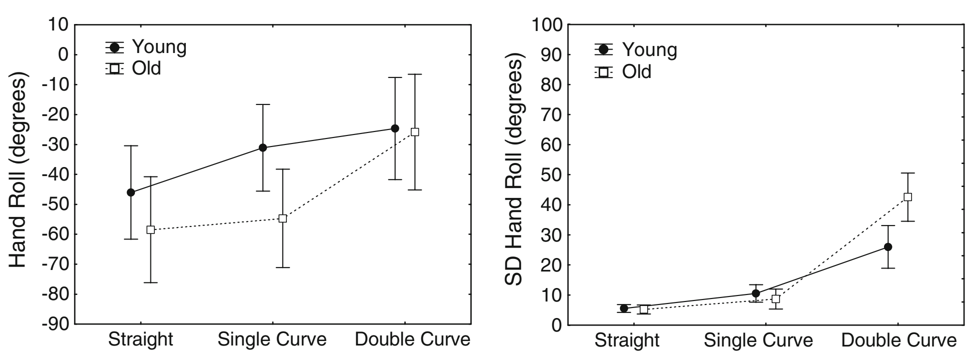

Fig. 6 Scatter plots of the average hand roll produced while removing the nut from each rod for the Young group (*solid circles*) and the Old group (*open squares*), and the average standard deviation of hand roll

For most simple motor tasks during daily life there is minimal or no opportunity for such practice.

Besides performing the task slower than young adults, the old adults in our experiments consistently demonstrated increased contact between the nut and rod compared to young adults. Large vertical forces are expected when subjects, old or young, are asked to quickly remove the tight fitting nut from the curved rods. It is not surprising that subjects would fail to precisely follow the curved rods when instructed that speed was of the essence. The large vertical forces that the old adults demonstrated on the straight rod were unexpected, at least to us, and particularly when the old subjects were instructed that speed was not essential. The latter observation may be consistent with suggestions that age-related slowing of hand/arm movements (in a line drawing task) does not simply represent a strategic slowing to minimize error per se, but reflects a fundamental deterioration in movement control (Morgan et al. 1994; Bellgrove et al. 1998).

It is important to note that old adults were not significantly impaired in controlling the horizontal position of the nut. The horizontally directed forces on the straight rod were small for both groups, and did not differ between groups in size or steadiness. These observations are consistent with reports of little difference between old and young adults in the steadiness of isometric contractions of elbow flexor, and in the steadiness (standard deviations of joint acceleration) of slow concentric and eccentric anisometric contractions of elbow flexors at small loads (Graves et al. 2000). In light of the uniformly small horizontal forces, we believe that the essential difference in performance between the young and old subjects was a consistently increased tilt of the nut relative to the rod for the old subjects. This tilt bound the nut against the rod as the nut was lifted. Tilt would cause contact between the nut and rod at two opposing edges (top and bottom of the nut's internal cylinder), which increases the likelihood that the nut will bind against the rod and transfer more of the vertical lifting energy to a force pulling up on the rod. Although we have no direct measures of the nut's orientation, our observation that old adults performed the task with greater 'roll' positions of the hand dorsum (in the direction of forearm pronation) than did young adults is consistent with (but not proof of) the interpretation that old adults performed the task with greater tilting of the nut. Tilting of the nut was not obvious while watching the old adults during the experiment, most likely due to the tight clearance (1 mm) between the nut and rod and the small size of the nut. Also, we did not see the old adults touch their digits to the rods, and so we do not suspect that the increased vertical force was from the friction of dragging their hand against the rods. The friction generated by the contact between the nut and rod may have contributed to the observed slowing, but are not the sole explanation for the movement slowing in the Old group. We base this interpretation on the longstanding and extensive reports of behavioral slowing in old age along with the modest correlations between force and duration that we observed.

Our interpretation that old adults tilted the nut more than young adults is consistent with recent suggestions that reduced control over the external moments applied to objects during grasp is a feature of aging that may contribute to reduced manual dexterity (Shim et al. 2004; Cole 2006; Olafsdottir et al. 2007). Studies of pressing force (Cole 2006; Olafsdottir et al. 2007) and prismatic grasp (thumb in opposition to the remaining four fingers; Shim et al. 2004) suggest that age-related declines occur in the ability to control the external moments on grasped objects. The result may be "an impairment of rotational hand actions…" which "…may contribute to failure at a variety of everyday tasks relying on rotational hand action, including spilling the contents of a mug, failing to turn the key to open the door lock, producing poorly legible handwriting, etc." (p. 1498, Olafsdottir et al. 2007). To our knowledge the presence of tilting during functional grasp and manipulation tasks has not been reported in old adults. More direct kinematic and kinetic data of tilting during grasp and manipulation would help to address if declining control of rotational hand action results from the misapplication of force at the fingertips (cf. Shim et al. 2004; Cole 2006), versus forearm pronation/supination, versus movements of more proximal joints. For example, Tremblay et al. (2003) reported anecdotal observations that old adults appeared to increase their wrist and shoulder movements during performance of the Grooved Pegboard task "…when they tried to compensate for their inability to manipulate the pegs…" (p. 131). Finally, if controlling fingertip force direction is a problem in old age then tilting the nut may occur more when applying high grip forces, which is a behavior that has been reported for old adults performing gripping tasks when the object's mechanical properties are uncertain (cf. Kinoshita and Francis 1996; Cole et al. 1999; Cole and Rotella 2001).

The old adults' sustained and sizable contact with the rod also may reflect a preference for contact with the rod for guidance purposes, and/or greater problems in control of the nut orientation due to decreased tactile sensibility. Both old and young subjects may have preferred to maintain slight contact with the rod to increase stability of the hand and nut in the horizontal plane, similar to the effects on postural sway of light touch with the fingertips (Holden et al. 1994; Jeka 1997; Jeka et al. 1997; Lackner and DiZio 2000). Old adults can use light touch to reduce sway similar to young adults (i.e., by 40–55%), but do so with higher pressing forces with the fingertip (Tremblay et al. 2004). These investigators reported that young adults used pressing forces of about 0.3 N whereas old adults produced light pressing forces of about 1.2 N, which could not provide the mechanical stabilization needed for the sizable reductions in sway. Instead it is believed that tactile information from the fingertips provides additional information about sway that is used to control lower limb and trunk muscles (Jeka 1997; Jeka et al. 1997).

It has been argued that the amount of pressing force that old adults use during sway control is explained to some degree by their reduced tactile sensibility (spatial acuity thresholds) at the fingertips (Tremblay et al. 2005). The transduction, transmission, and central processing of tactile sensory information deteriorate in old age (Verrillo 1979; Kenshalo 1986; Cerella 1990; Schmidt et al. 1990; Stevens 1992; Gescheider et al. 1994a, b; Stevens and Patterson 1995; Gescheider et al. 1996; Stevens et al. 1998; Tremblay et al. 2003, 2005; Manning and Tremblay 2006) which raises the possibility that old adults either generated or permitted greater lifting forces on the rod because of a reduced ability to detect those forces at the fingertips. Cole and Rotella (2001) reported that old adults' threshold was twice that of young adults for responding with increased grip force to pulling loads that were applied to a grasped object. This estimate of the threshold for responding to tangential forces at the fingertips was based on regressions of response latency against load rate. A reduced sensitivity to tangential loads at the skin of the fingertips may have contributed to the large vertical forces seen in the present experiment because the old adults would have to experience greater friction between the nut and rod, and hence greater tangential forces on the skin via the nut, before responding with changes in nut orientation. These increased frictional forces also could account for some movement slowing as well, which is consistent with the modest correlations between movement duration and force impulse in the old subjects, but not in the young subjects. However, we cannot determine how much of the old adults' considerable slowing occurred due to frictional forces opposing the lift forces. From the modest correlations noted above we can speculate that the slowing in the task and the suspected tilt of the nut may be related, though not strongly.

The evidence that the old adults may have tilted the nut more than young adults also raises the possibility that aging is associated with a reduced ability to encode/decode sensory (peripheral afferent or efferent-copy) information related to the orientation of grasped objects. Tactile shape perception has been studied in primates, which indicates that three-dimensional shape is processed in Brodmann's area 2 and in secondary somatosensory cortex (SII) by integrating cutaneous and proprioceptive inputs (Hsiao 2008). It would be reasonable to assume that this capacity deteriorates in old age, given that the capacity to perceive the orientation of gratings scanned with the fingertips deteriorates in old age (Stevens et al. 1998; Tremblay et al. 2003).

The ability to determine the orientation of grasped objects relative to the hand or gravity also may depend on the encoding and decoding of information concerning the magnitude and direction of forces at the skin contact patches with the object. The brain is informed about the directions of forces at the glabrous skin by signals from at least three types of mechanoreceptive tactile afferents (fast adapting with small receptive fields, FA-I; slow-adapting with small receptive fields, SA-I; and slow-adapting with large receptive fields, SA-II; Birznieks et al. 2001). Deteriorating function of FA-I and SA-I afferents in old age is well known from psychophysical studies of vibration sense and spatial acuity (Stevens et al. 1998; Tremblay et al. 2003). Manning and Tremblay (2006) also have documented age-related deterioration of tactile pattern recognition at the fingertip (letter recognition) that they suggest is the result of changes in peripheral signals and central processing. Determining the orientation of objects within grasp also may depend upon the ability to monitor dynamic changes in the locations of edges and curves against the skin. Grasped objects with curves evoked responses in SA-I, SA-II, and FA-I afferents from skin over the terminal phalanx, with discharge frequencies that correlated with curvature (Jenmalm et al. 2003). Reduced density of tactile receptors at the hand in old age (Cauna 1965) therefore may impair the ability to determine the spatial relationship between the hand and object. However, curvature and force direction had interactive effects on afferent discharge rate, which prompted the authors to conclude that "…the CNS must possess mechanisms that disentangle interactions between these and other parameters of stimuli on the fingertips." (Jenmalm et al. 2003). Hence, old adults may be impaired additionally if aging affects the CNS mechanisms for 'disentangling' these complex stimulus interactions during grasp.

Summary and conclusions

We have observed that old adults perform the rod-and-nut task slower than young adults, and with higher vertical contact forces, even when allowed to move at self-selected 'comfortable' speeds. Both groups exerted similar horizontal forces, which suggest that old adults tilted the nut more, regardless of performance speed. We believe that these observations support suggestions that aging is associated with a fundamental problem controlling the external moment applied to grasped objects. The failure of the vertical forces to decrease much at slower movement speeds indicates that slowing does not represent a compensatory strategy for this tilt. The tilt may arise from deteriorating sensorimotor mechanisms, from a preference to maintain contact with the rod for guidance, or for reasons we have not yet considered.

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