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A STRATEGY OF FASTER MOVEMENTS USED BY ELDERLY HUMANS TO LIFT OBJECTS OF INCREASING WEIGHT IN ECOLOGICAL CONTEXT

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Abstract—It is not known whether, during the course of aging, changes occur in the motor strategies used by the CNS for lifting objects of different weights. Here, we analyzed the kinematics of object-lifting in two different healthy groups (young and elderly people) plus one well-known deafferented patient (GL). The task was to reach and lift onto a shelf an opaque cylindrical object with changing weight. The movements of the hand and object were recorded with electromagnetic sensors. In an ecological context (i.e. no instruction was given about movement speed), we found that younger participants, elderly people and GL did not all move at the same speed and that, surprisingly, elder people are faster. We also observed that the lifting trajectories were constant for both the elderly and the deafferented patient while younger participants raised their hand higher when the object weighed more. It appears that, depending on age and on available proprioceptive information, the CNS uses different strategies of lifting. We suggest that elder people tend to optimize their feedforward control in order to compensate for less functional afferent feedback, perhaps to optimize movement time and energy expenditure at the expense of high precision. In the case of complete loss of proprioceptive input, however, compensation follows a different strategy as suggested by GL's behavior who moved more slowly compared to both our younger and older participants.

Key words: motor control, proprioception, aging, deafferentation.

INTRODUCTION

During daily activities involving the manipulation of objects, humans have to interact with the objects' extrinsic (position, orientation) and intrinsic characteristics (texture, shape, mass). Furthermore, when displacing an object, the motor system has to deal with its inertial forces and its weight (i.e. the gravitational forces that act on the mass) (Johansson and Flanagan, 2009). From these, the central nervous system (CNS) must construct an appropriate motor plan to achieve the goal. It seems that the CNS relies on sensory information obtained in real time as well as on internal models based on prior interactions between the body and the environment to compute the optimal command of the arm for pointing (Le Seac'h and McIntyre, 2007; Gaveau et al., 2014) and for lifting (Nowak and Hermsdörfer, 2003). Thus, it is usually assumed that grasping and lifting an object is programed in accordance with the object's weight.

Data supporting this assumption have mostly been obtained with the experimental paradigm proposed by Johansson and co-workers (Johansson and Westling, 1988a, 1988b; Gordon et al., 1991; Johansson et al., 1992b; Flanagan et al., 2001), in which an instrumented object is used to simultaneously measure grip and load forces (Gordon et al., 1993; Wing et al., 1996). When the subject knows the object's weight (e.g. when trials are performed in blocks during which the weight does not change), grip forces and load forces develop in parallel until the moment of lifting, thus demonstrating an anticipatory control of coordination. When the mass to be lifted is changed unexpectedly, however, (i.e. if the weight is heavier than expected) the load force develops in several steps with increased gripping force. These fast corrections are triggered by inputs from cutaneous finger afferents activated by pressure between the object and the skin of the finger (Johansson and Humphrey, 1991). Digital anesthesia, depriving the subject of such afferent signals, resulted in increases of the overall grip force and changes in grip-force/load-force coupling (Nowak et al.,

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Abbreviations: CNS, central nervous system; HO, heavy object; LO, light object.

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2001). Similarly, a deafferented patient (GL) deprived of both cutaneous and proprioceptive information nevertheless showed scaling of grip force to load force, although the precise relationship between both forces differed from the control group (Hermsdörfer et al., 2008). This can be explained by the importance of this type of information in the choice of appropriate motor parameters for the feed-forward command and also for the feedback correction of erroneous movements. Fleury et al. (1995) suggest that, whatever the weight, a functionally deafferented patient (GL) uses the same motor program for lifting objects of different weights, as evidenced by the identical grip force pulses she uses in all cases.

Correct modulation of grip force is not the only reason why the CNS may need to accurately estimate the mass of an object held in the hand. When moving from one point to another, hand trajectories are generally straight (Morasso, 1981) or slightly curved (Atkeson and Hollerbach, 1985) with a bell-shaped velocity profile (Morasso, 1981; Flash and Hogan, 1985). Moreover, the velocity profile tends to be symmetrical over a range of different inertial loads (i.e. for different masses held in the hand) and movement velocities, although this so-called invariant characteristic can change according to the direction of movement with respect to gravity (Papaxanthis et al., 1998, 2003), or the viscosity of the environment (Jaric et al., 1998, 1999). In order to produce the stereotypical hand trajectory, the CNS must anticipate the mass of the hand-held object in order to program muscle activations that will accelerate and decelerate the hand appropriately (Flanagan et al., 2001).

Advancing in age leads to a slowing in synaptic transmission and conduction velocity due a degenerative process affecting both motor and sensory fibers (Desmedt and Cheron, 1980; Doherty et al., 1994). This phenomenon is, at least partially, responsible for the loss of tactile acuity (Stevens and Choo, 1996), joint position sense and kinesthetic movement sense (for a review of proprioceptive sensibility in elderly subjects see Goble et al. (2009)). Thus, because of this deterioration in sensorimotor processing, accompanied by weaker force production, older adults are generally slower in executing movements (Welford et al., 1969) with an increase in movement variability (Lyons and Elliott, 1996). Several studies have suggested that elderly adults have to change their motor strategy (Pratt et al., 1994) because they need more time to obtain reliable feedback for maintenance of speed-accuracy relationship (Bennett et al., 2012). But, in these studies, the task was required to be both accurate and fast. In this context, the observed difference in kinematics could be assigned to longer online corrective-action durations in elderly rather than to different control strategies *per se* as compared to younger people (Welsh et al., 2007). It is therefore interesting to study the motor behavior of elderly subjects in an ecological, rather than constrained, condition.

The experiment presented here was designed to test which motor strategies are used to program dynamic arm movements of lifting object in case of normal, limited and quasi absence of available proprioceptive sensory information. To that end, we selected a group of young people (average age: 29 years), a second group of older individuals (average age: 64 years) and a deafferented patient (GL, 64 years) to participate in our experiment. GL was chosen due to her almost complete loss of proprioceptive information resulting from her pathology. In the other healthy participants, we postulated that available sensory information might also vary as a function of age (Corbin and Gardner, 1937) and that this fact could have some influence in the control and programing of their movement. The comparison of GL, young healthy and older people represents then a unique case of study of the role of sensory information (in particular proprioceptive input) to control the movements. In particular, we wanted to test the idea that total absence of proprioception (sensory deprivation) induces a motor strategy that resembles that encountered in aged subjects.

In these experiments we used relatively heavy objects (900 g and 300 g) of the size of a glass that had to be handled with the whole hand, as opposed to the precision grip used in some studies (Johansson and Westling, 1988a; Gordon et al., 1991; Johansson et al., 1992b; Flanagan et al., 2001). Our purpose was first, to analyze the kinematics of the lifting movement itself, an aspect of grasping coordination which has received little attention so far; second, to investigate a situation where the weight was uncertain and could not be anticipated and third, to determine the role of proprioceptive afferents in the programing and control of goal-directed lifting movement.

Our protocol put the subject in a situation where visual clues about the object's weight were not available and no constraint was imposed about movement velocity, thus falling into an ecological context. By comparing the kinematic parameters produced by young and elderly people with the hand trajectories produced by the deafferented patient GL, we examined how tactile and kinesthetic feedback may influence the control system when the object's mass is uncertain. Finally, in these experiments we investigated the mechanisms used by the CNS to solve the problem of lifting an object of known or unknown weight with the help of a mathematical model that simulates the generation of trajectory according to the different forces applied to the object (feed-forward force developed by the subject, gravity, viscosity and stiffness).

EXPERIMENTAL PROCEDURE

Seven healthy younger adults (23–35 years old, mean 29) and seven older individuals (59–71 years old, mean 64) participated in the study. The participants did not have any sensory or motor impairments, although, subclinical sensory-motor alterations linked to fiber loss may compromise optimal transmission of peripheral signals (Corbin and Gardner, 1937). In addition, we compared their performance to those of GL (64 years old) who suffers demyelination of large-diameter afferent fibers supplying the CNS with information from muscle spindles, Golgi tendon organs and cutaneous sensors (for more details see Forget and Lamarre (1987)). All participants gave their information consent according to the ethical standards of the 1964 Declaration of Helsinki.

Task

The task consisted of reaching and grasping with the right (always dominant) hand, a cylindrical object placed on a table in front of the subject and lifting it onto a shelf located 10 cm leftward and 18 cm above the table (Fig. 1A). The objects were visually identical, in the form of cylindrical opaque containers (8 cm height, 7 cm diameter, volume 0.176 l) weighing respectively 0.3 kg for the light object (LO) and 0.9 kg for the HO. Subjects were not informed that there were two visually identical objects with different weights. The subject sat comfortably on a chair in front of the table, with the abdomen at 10 cm from its front edge, keeping his/her right hand on the abdomen, slightly below the level of the table. Electronic translucent glasses (Plato glasses, Translucent Technologies Inc.) and ear covers prevented the subject from seeing or hearing the manipulation of objects by the experimenter. One of the objects was placed by the experimenter in front of the subject at 20 cm from the edge of the table, while the other remained hidden behind a screen.

Trials were manually triggered via a computer that initiated the recording and then, after a random duration time (0.5–1.5 s), rendered the glasses transparent. The subject was instructed to reach and grasp the object as soon as the translucent glasses became clear, to place it on a circular mark (8 cm of diameter) drawn on the shelf (18 cm height 32 cm deep and 19 cm large), and finally to resume his/her resting position. The initial position of the object was 23 cm away of the target in the anterior direction, 3.5 cm in the medial direction and 18 cm in the height axis. The instruction was to ‘‘act naturally”, without emphasis on precision or velocity. The movement period lasted 4 s, allowing the subject to visually monitor his/her entire movement before the glasses became translucent again.

The movements of the object and of the subject's hand were recorded using a Polhemus Patriot system. This system measured the position in space, sampled at 60 Hz, of each sensor along a reference axes system centered in the middle of the transmitter which was located at 50 cm on the right of the subject, defining a Cartesian frame where X is rightward, Y forward and Z upward. One sensor was fixed on a removable cover, which could be attached to either the light or heavy object. A second electromagnetic sensor was fixed by adhesive tape on the dorsum of the right hand. To avoid interference with the measurement system, all metallic objects and electromagnetic sources were carefully removed from the experimental environment. A custom-made Labview (National Instruments) software was used to manage the experiment and to record the data from the Polhemus tracker.

Each recording session included a total of 41 trials, beginning with 10 trials with the LO not used in the analysis, followed by a sequence of 31 trials in which participant could not know the weight of the object prior to the start of the trial (Fig. 1B). Thus we induced two main conditions of weight (light object, **LO** and heavy objects **HO**) and a specific trial called **Surprise** where the expected weight of object was suddenly heavier than expected because it was preceded by a set of LO trials in the beginning of the experiment.

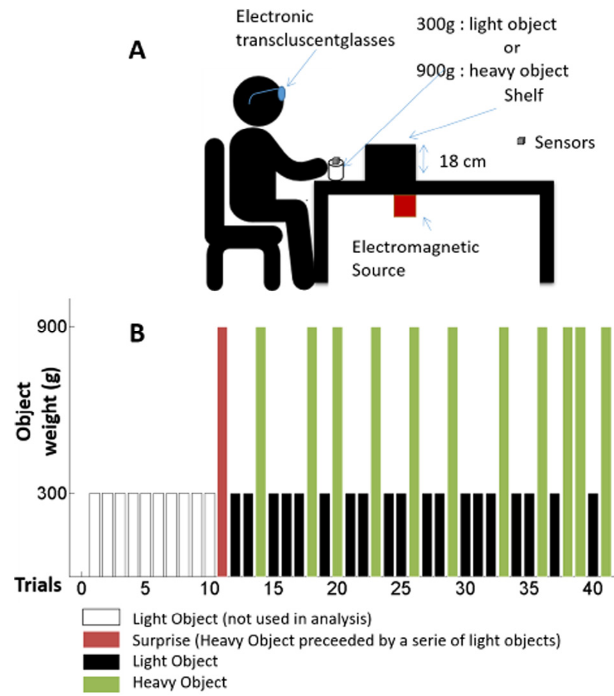

Fig. 1. (A) Experimental set-up and task. The subject had to reach and lift a cylindrical object from the table to the target shelf, 18 cm above. Electromagnetic sensors located on the right hand and over the object were used to record the movement. The opening of the translucent glasses triggered the hand to move toward the object. (B) Sequence order presentation. The participant had to move a cylindrical object (A) with two different weights (light object LO 300 g and heavy object HO 900 g) but identical visual appearance. Surprise, refers to the first presentation of HO after a sequence of the first 10 presentations of LO (not analyzed).

The experiment with GL was not carried out in our laboratory and thus was performed with different, albeit functionally equivalent, hardware. We used a portable Polhemus Fastrak recording device which measured the movements, sampled at 30 Hz, of 2 electromagnetic sensors placed in the same way as for the control participants (i.e. on the object, on the dorsum of the hand).

Data analysis

The data were filtered using a Gaussian low-pass filter (cut-off frequency: 7 Hz) and the velocity and acceleration were computed by derivation of position with respect to time. As the task mainly involved lifting the object in a vertical frontal plane we mainly focused our analysis on the vertical axis (Z). Observations in this axis are particularly appropriate in this study because it may reveal the motor adaptation strategies made by participant to counteract the effects of gravity upon weighted objects. To simplify the analysis, we decomposed the overall movement into five distinct steps (Fig. 2), defined as follows. The reaching phase of the movement of the hand was composed of a fast upward phase toward the object until the maximal height of the hand trajectory. Then began the grasping to load phase, in which the hand goes down, grasps the object then remains stationary while gradually generating an upward force. When the applied upward force was greater than the weight of the object, the lifting phase began during which the hand and object accelerated upward (accelerated lifting) then decelerated until reaching a maximal height (decelerated lifting). The object was then lowered and placed on the shelf (placing phase).

Statistical analyses

For each kinematic variable, we analyzed the differences between young and elderly groups of subjects using a non-parametric Mann and Whitney U test (Table 3) (kinematic mean values per subject selected as dependent variables and population selected as independent variables) because normality was not assumed for the distribution. Indeed, a Shapiro–Wilk test was used to test the normality of the distribution over the different variables and this test was significant in some variable revealing that kinematic values were not all distributed normally across the population, perhaps reflecting two or more strategies among individuals (results not shown). To compare GL results with young and other elderly, healthy participants, we did not use a statistical test *per se*. Rather, we compared GL's mean value of each variable with the tolerance interval (mean ± 1.96 * standard deviation) of values in young and older populations. If the values of GL were outside the boundaries of tolerance interval of values of the other populations, we considered her variable values as being reliably different. This test was chosen because in a normal population 95% of the distribution falls between mean ± 1.96 * standard deviation (Whitley and Ball, 2002). A similar methodology was used previously by Hermsdörfer et al. (2008) to compare control participants with two deafferented patients. This analysis is referred to here as an analytic comparison (rather than statistical analysis). To differentiate clearly these two types of analyses, statistically significant differences are indicated in the figures and tables with $^{*}p < 0.05$ or $^{**}p < 0.01$ and analytic differences with a '≠' symbol.

Additionally we computed a statistical power analysis using G * Power 3.1 software (Faul et al., 2007). This tool is used to compute an effect size and the power of a statistical test. This so-called post hoc power analysis permits one to reveal the validity of our statistical test according to standard values of d and power (Cohen, 1988). The results of the test can thus be considered when d is large (> 0.05) and power is close to 1.

Within the young and elderly groups we performed a second statistical analysis using Friedman ANOVA test to reveal possible differences between kinematic values and load conditions (LO, HO and surprise). To handle the fact that the number of trials inside each condition was different, we performed the analysis using the mean of each variable per subject and condition (except for surprise where the unique value was chosen per subject). Post-hoc Conover comparisons were then used to identify possible differences between pairs of conditions (Tables 4 and 5). GL's mean measures were also computed and referred in Table 2. For each statistical post hoc test used we computed another post hoc power analysis with G * Power (Faul et al., 2007) to reveal the size effect and the power of our statistical analysis.

Model

We developed a computational model, adapted from McIntyre and Bizzi (1993), to understand how participants and GL might adapt to the different weights in transport lift. As input, this model required a desired trajectory representing an "ideal" movement (Bizzi et al., 1984; Flash and Hogan, 1985) that would be performed without external or internal constraints. To avoid any assumption concerning the estimated trajectory we defined this pattern as the mean of curve off all participants excluding GL and surprise trials (*XD*). Desired Velocity (VD) and Acceleration (AD) Profiles were calculated by applying derivation upon the desired trajectory respectively 1 time for the velocity and 2 times for the acceleration. This mean curve pattern was passed through an inverse model of the limb dynamics (Atkeson, 1989; Kawato, 1999; Davidson and Wolpert, 2004), including the estimated mass (*Me*) of the object to generate the primary force that would nominally drive the hand and object along the desired path. Applied forces were then modulated during the course of the movement by the object's true weight (real mass of the object (*Mr*) on which gravity is applied) by the neural feedback mechanisms and the viscoelastic properties of the musculo-skeletal system (Eqs. (2)(4)). These forces were gathered to finally calculate the real acceleration profile at each time frame (Eq. (1)). Real trajectory (*XR*) and Velocity profile (*VR*) are then calculated according the Euler method (Eqs. (5) and (6)).

$$AR_{(t)} = (FF_{(t)} + S_{(t)} - I_{(}t) - W)/Mr \tag{1}$$

where

$$FF_{(t)} = Me * AD_{(t)} + G * m \tag{2}$$

$$S_{(t)} = k * (XD_{(t)} - XR_{(t)}) \tag{3}$$

$$I_{(t)} = b * (VD_{(t)} - VR_{(t)}) \tag{4}$$

$$VR_{(t)} = VR_{(t-1)} + AR_{(t-1)} * d \tag{5}$$

$$XR_{(t)} = XR_{(t-1)} + VR_{(t-1)} * d \tag{6}$$

where AR: real acceleration profile; FF: Feedforward force applied to the object; Me: Estimated mass of the object; AD: Acceleration from the estimated profile; VD: Velocity from the estimated profile; *G*: Gravity constant of 9.80 m·s^{-2}; *S*: stiffness force depending of the muscle length; *k*: stiffness gain parameter; XD: estimated trajectory; XR: Real trajectory; *I*: viscosity force depending of the speed of the muscle; *b*: viscosity gain parameter.

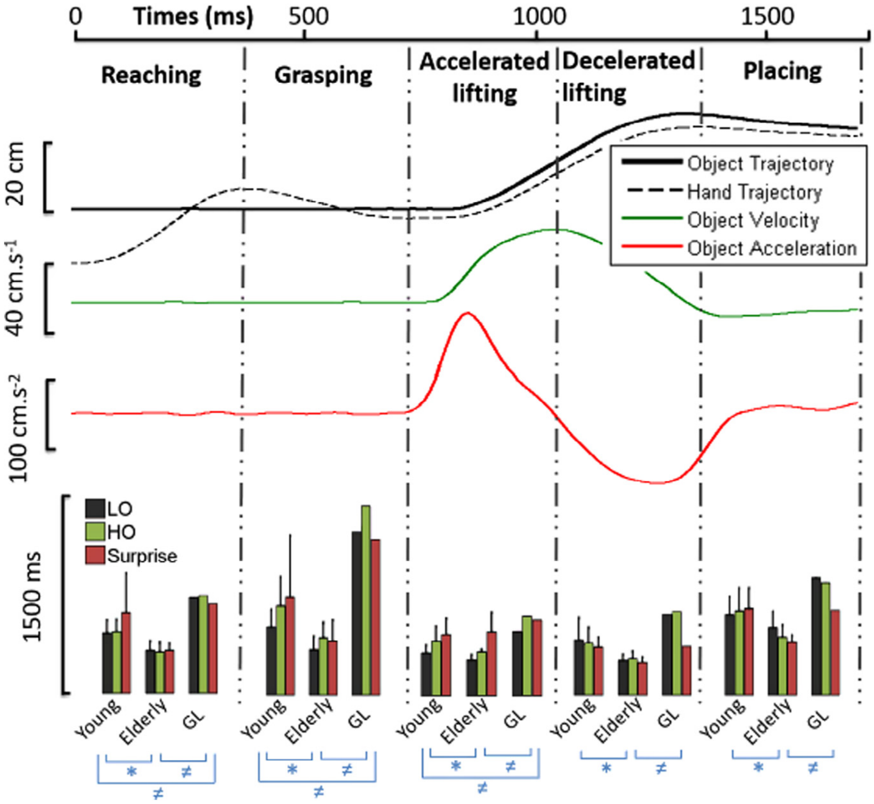

Fig. 2. Upper part: Vertical trajectory and velocity profile of the hand and object's movements used to delimit the successive phases of action: The reaching phase is initiated with hand departure until the time when the hand is as its maximal amplitude). In the grasping to load phase forces opposed to the inertia of the object are developed until the departure of the object from the table. Lifting consists of an acceleration (accelerated lifting) and deceleration (decelerated lifting) component. Finally, the object is placed on the target (placing phase). Lower part: Mean and standard deviation of the duration of each phase for LO and HO and Surprise trials. * symbol means a highly statistical difference ($p < 0.01$) between young and elderly populations and $\neq$ refers to analytic difference between GL and other participants (see methods for more details).

To make predictions with the model, it was necessary to select the values of the free parameters in a reasonable manner such that the behavior of the model would be representative of what is done by the human arm. We carried this out as follows: The reference trajectory was obtained as the mean trajectory obtained with the recorded trials of all participants except GL (as stated above). To approximate the physiology of the system, we set Mr to 1.8 or 2.4 kg, representing the mass of object (0.3 or 0.9 kg) added to the mass of the forearm ($\sim$1.5 kg). Me could take either one of these two values or an intermediate value of 2.1 kg (i.e. a 1.5-kg arm plus an intermediate mass of the object equal to 0.6 kg). We tested 3 different values of k (5, 25 and 50 N/m) and viscosity parameters were then programed to evolve with stiffness so as to keep a constant damping ratio of 0.707 (Hogan, 1984) (Eq. (7)).

$$\textit{damping ratio} = \frac{b}{2\sqrt{k \cdot Me}} = 0.707 \qquad (7)$$

Eq. (7): damping ratio according to viscosity (b) and stiffness (k) is kept constant according to Hogan (1984).

All these parameters were set in accordance with the estimated mass of the object (Me) thus reflecting the subject's planned motor command. Once the lift started, the object was submitted to feedforward force, feedback force and its true weight (Mrg). The output trajectory was computed by integrating the equations of motion ($F = ma$) with the different applied forces. Fig. 3 shows the output of the model in terms of hand trajectory and velocity in the vertical direction. Traces show the nominal trajectory for a correct *a priori* estimate of Me, the effects of overestimating or underestimating the mass when computing the feedforward command, and the effects of greater or lesser stiffness and damping (i.e. for a higher or lower natural frequency). Trajectories predicted by the model were submitted to the same analysis as the empirical data obtained from human subjects.

Our goal for this simulation was not to precisely reproduce the full complexity of the human arm, but rather to gain insight into the feedforward and feedback mechanisms used by the CNS to account for varying load mass when moving the limb. In our highly simplified model, the estimation of the mass Me of the object to be lifted was used to calculate the feedforward force necessary to generate the movement. More specifically, feedforward forces were composed of forces needed to accelerate the mass of the object, forces needed to counteract gravity's pull on the mass and forces need to overcome the viscosity of the system. The automatic feedback part of the model was composed of stiffness and viscosity, both presumed to have been set prior to movement onset and constant throughout the movement. Stiffness was defined as the parameter k (called the stiffness gain parameter): the more the difference between desired and actual trajectory, the more the stiffness modulated the applied force to bring the actual trajectory closer to the desired trajectory. Viscosity was calculated from a parameter b (called the viscosity gain parameter). In this model, viscosity always impeded the movement according to the instantaneous velocity.

EXPERIMENTAL RESULTS

Kinematic variables in each group

When comparing kinematics between young and elderly people, we found significant differences in every variable except for reaction time, maximal amplitude and placing duration (Table 3). Reaching duration was shorter in elderly when compared with younger, as well as grasping to load duration, accelerated lifting duration

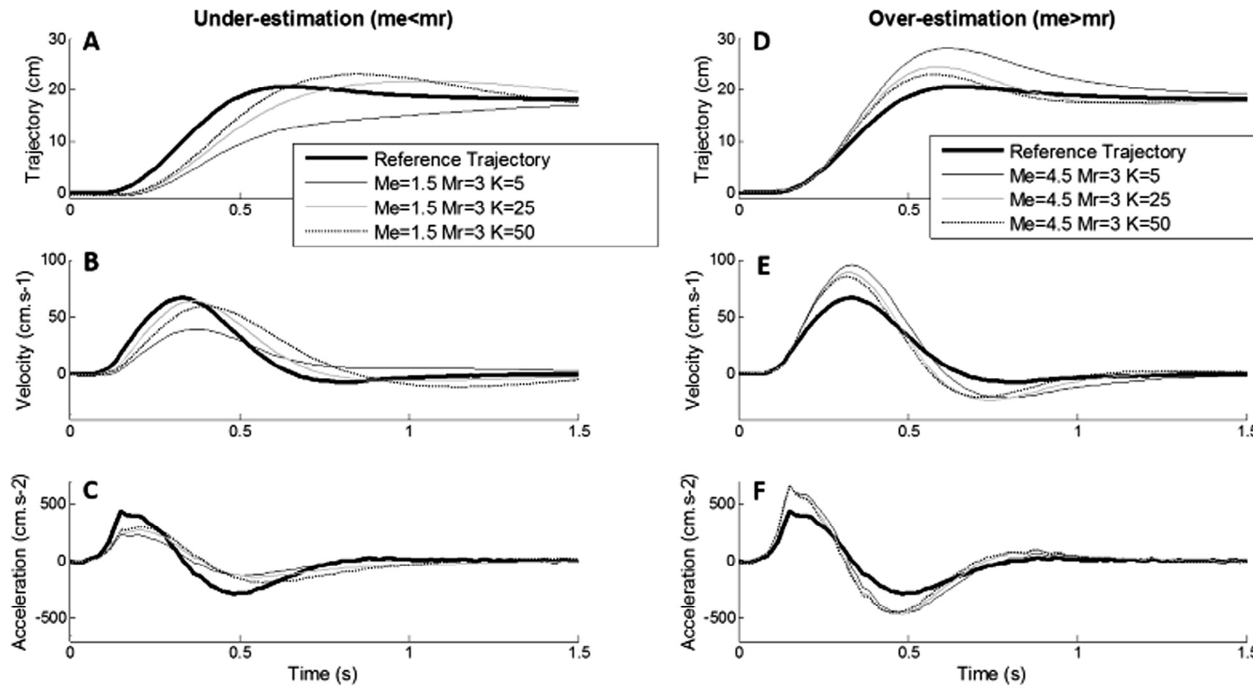

Fig. 3. Effect of the model when modifying, estimated mass (me), stiffness and viscosity (k). The left column graphs (A, B, C) correspond respectively to the trajectory, velocity and acceleration profiles when the estimated mass ($Me = 1.5$) is lower than the actual mass of the object ($Mr = 3$). The right column graphs (D, E, F) correspond to kinematic profiles when the estimated mass ($Me = 4.5$) is higher than the actual mass of the object ($Mr = 3$). In each graph, 3 different lines were generated according to different parameters of damping ($k = 5$, $k = 25$, $k = 50$). The reference trajectory (or planned trajectory) is obtained by the mean of all movements made by young and older participants.

and decelerated lifting duration. Consequently, both mean velocity during the whole movement and maximal peak velocity during lifting were higher for older people. Symmetry ratio (acceleration time divided by deceleration time), which is an important factor describing human motor control (Jaric et al., 1998) was higher in our elder subjects than for younger participants meaning that elderly people spend more time decelerating than accelerating while our younger participants showed the opposite.

When comparing GL's variable values with young and older people it appeared that GL spent more time in the execution of reaching, grasping and accelerated lifting phase of the movement (Table 3 and Fig. 2 lower plots). Additionally GL was also slower in executing deceleration of the lifting compared to the older group of participants. According to our analytical comparison with the older group, GL displayed higher reaction times and longer deceleration of lifting and lower mean movement velocity, peak movement velocity and symmetry ratio (Table 3 and Fig. 4A). Another interesting result is that the amplitude of her movements was not higher than our younger group (Table 3 and Fig. 4B). Generally, GL differed more with respect to the older group than to the younger group (Table 3, Fig. 2 lower plots and Fig. 4).

To understand the overall behavior of the 3 groups, we used the model described above to predict the observed kinematics (Fig. 5 and Table 1). We have determined that the main differences described for each variable could be ascribed to a different kind of pre-programing of the movement. In particular it is possible to partially reproduce the movement patterns across subject groups by modifying the estimated mass of the object that had to be lifted. We assumed that the estimated/desired trajectory would be the same among subjects (everyone would produce the same invariant trajectory, if possible), which we set as the mean of all young and older subjects, combined, and then examined the effects of varying the estimated mass of the object specifically for each group of subjects. In line with preceding results (Table 3, Figs. 4 and 5A–C), we assumed that younger people tend to slightly underestimated the mass of the object to be held whereas older people tend to slightly overestimate it and that GL deeply underestimates it. We then ran the simulation three times with the same reference trajectory, the same mass of the object ($Mr = 2.1$ which correspond to the mass of the arm (1.5 kg) and of the object (0.6 kg, i.e. an intermediate mass between LO = 0.3 kg and HO = 0.9 kg)), the same stiffness ($K = 7$) while varying the estimated mass of the object according to our assumptions ($Me = 1.8$, $Me = 2.3$, $Me = 1.2$ for younger, older and GL's simulations respectively) (Fig. 5D–F). Viscosity (B) was computed so as to keep a constant damping ratio according to the parameter K and Me (Eq. (7)). By a slight underestimation of the object weight ($Me < Mr$), feedforward forces were not sufficient to follow the desired trajectory. As a consequence, maximal height was lower than expected; durations of the movement phases were longer and thus the velocity/acceleration tended to decrease. In contrast a slight over-estimation

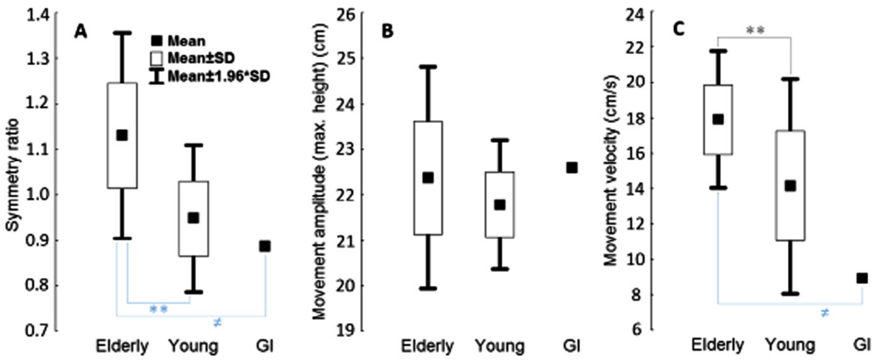

Fig. 4. Mean and standard error of symmetry ratio (A) maximal amplitude (B) and mean movement velocity (C) of movements in each category of population. Mann-Whitney U test and analytic comparisons were used to test difference between young and older values. Significant differences were marked by ** ($p < 0.01$) or * symbol ($p < 0.05$). Analytical difference was marked with a ≠ symbol (see experimental procedures and Error! Reference source not found.)

of weight ($Me > Mr$) implied a higher height and shorter duration of the movement with an increase in velocity/acceleration profiles. Consistent with a pronounced underestimation of object mass ($Me \ll Mr$), it was also possible to predict GL's very slow movement characteristics in duration and amplitude (and thus velocity and acceleration). Kinematic values were then computed over experimental and model curves (Table 1). The weak differences between experimental kinematic and predicted kinematics for each group indicates that the overall behavior of each group can be modeled by changing the expectation that is made upon the mass of the object to be transported. Please note also that experimental values from Table 1 may change with those obtained from Table 3 because they were directly computed on the mean curve of each population (Table 3 values were obtained from the mean values of individual plots).

Evolution of kinematics in relation to weight and sequence

Of great interest in this study are the potential differences that may arise between the weight and presentation order. Indeed a significant difference between the two conditions of weight (LO and HO) and sequence (Surprise) would indicate how changing weight and sequence order affects the control of the movement depending on whether the subject takes into account his/her previous experience with the hand-held load (Fig. 6).

Younger subjects

Using Friedman ANOVA associated with a pairwise Conover comparisons test for younger participants only, we found significant differences between LO and HO

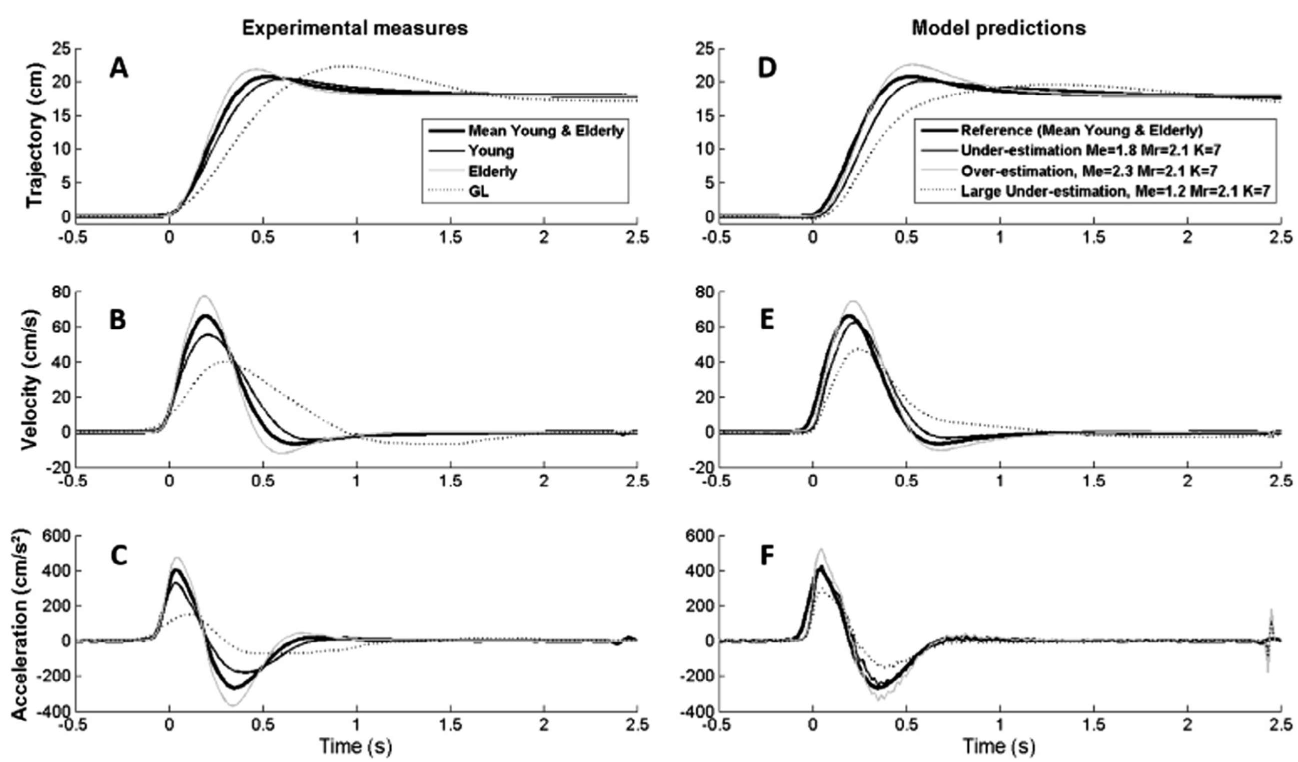

Fig. 5. Kinematic mean plots of transport movement in each population obtained experimentally (left column graphs A, B, C) and model predictions (right column graphs D, E, F) obtained with various parameters object weight expectation (m_e) and damping (k). With the described model we mainly explain kinematic profiles in our young participants by a slight under-estimation of object weight whereas the opposite was found in elderly population. The experimental results of GL were mainly explained by a large under estimation of object weight.

Table 1. Kinematic values obtained from model predictions according to the different population hypotheses upon movement strategies. These values were obtained from the plots of Fig. 5 using the same methodology employed for getting kinematic values from experimental results (see Experimental procedure)

	Acceleration Duration (ms)	Deceleration Duration (ms)	Place Duration (ms)	Maximal Amplitude (cm)	Velocity Peak ($cm{\cdot}s^{-1}$)	Velocity Mean ($cm{\cdot}s^{-1}$)	Symmetry ratio
Reference	250 (exp)	333 (exp)	400 (exp)	20.72 (exp)	66.16 (exp)	18.72 (exp)	0.75 (exp)
Young	233 (mdl)	383 (mdl)	183 (mdl)	20.10 (mdl)	62.67 (mdl)	24.03 (mdl)	0.61 (mdl)
	283 (exp)	400 (exp)	350 (exp)	20.40 (exp)	55.29 (exp)	18.20 (exp)	0.71 (exp)
Elderly	233 (mdl)	317 (mdl)	533 (mdl)	22.48 (mdl)	74.34 (mdl)	16.95 (mdl)	0.74 (mdl)
	233 (exp)	283 (exp)	433 (exp)	21.79 (exp)	77.22 (exp)	18.96 (exp)	0.82 (exp)
GL	217 (mdl)	1067 (mdl)	767 (mdl)	19.54 (mdl)	47.22 (mdl)	8.83 (mdl)	0.20 (mdl)
	433 (exp)	633 (exp)	767 (exp)	22.21 (exp)	40.04 (exp)	8.72 (exp)	0.68 (exp)

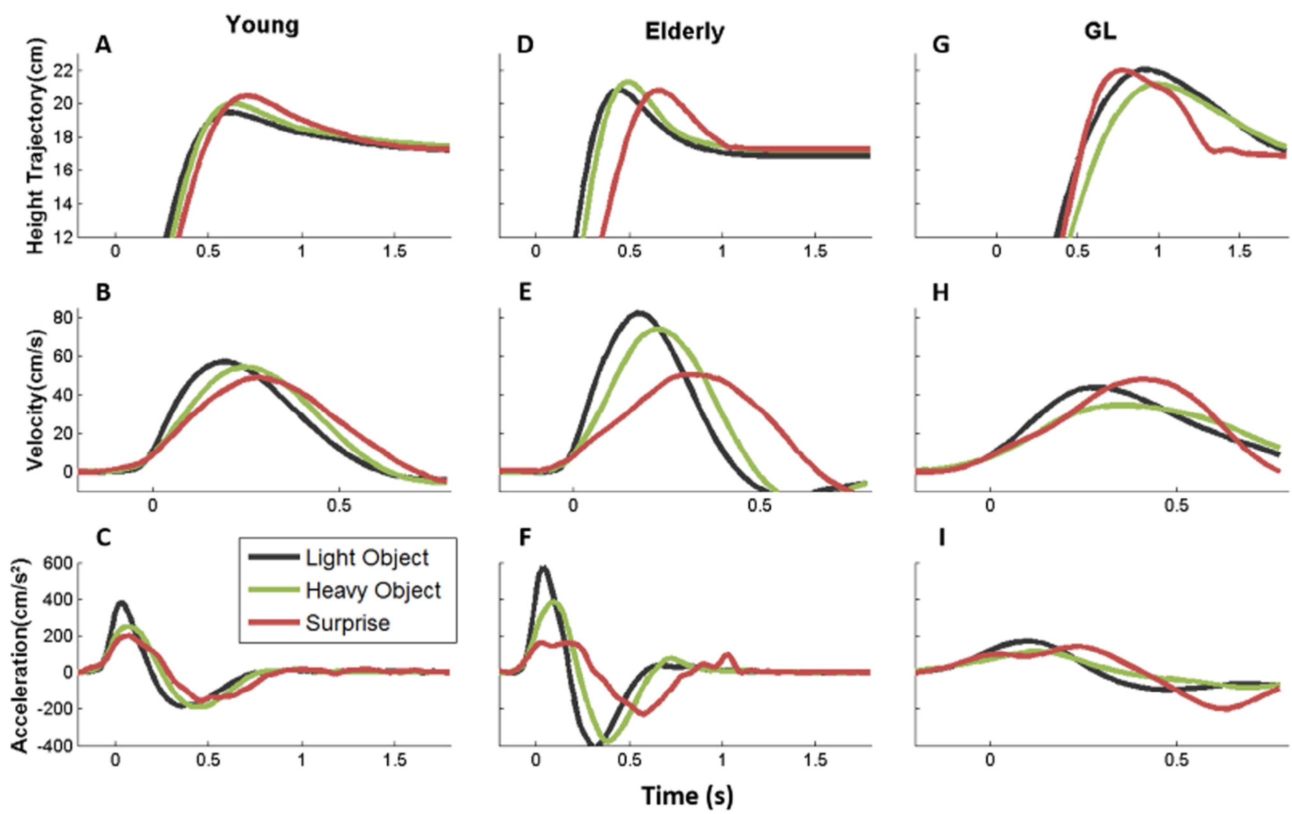

Fig. 6. Kinematic profiles (trajectories in upper line graphs (A, D, G), velocity profile in middle line graphs (B, E, H), and acceleration profile in the third line graphs(C, F, I)) of object transport obtained experimentally in the 3 populations (young in the left column graphs (A, B, C), elderly in the middle column graphs (D, E, F), GL in the last column graphs (G, H, I)). Within each graph, the mean of each sequence condition were plotted (LO for light object in black, HO for heavy object in green and Surprise in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

conditions in loading duration and maximal amplitude (Table 4). A tendency toward significance was also found concerning acceleration duration. This analysis indicated that (1) loading and acceleration duration were longer for heavier objects; (2) maximal amplitudes were higher for heavier objects (Fig. 5A–C). Surprise trials were longer than other LO trials in loading duration and acceleration duration but were not much different than HO trials (beside there is a tendency for significance for accelerated lifting duration). Moreover, Surprise trials were higher to both LO and HO trials (Fig. 7).

Older subjects

Statistical analysis using Friedman ANOVA for older participants revealed a significant difference among loading duration, accelerating time duration, placing duration, and symmetry ratio between weight and order conditions (LO, HO and Surprise) (Table 5). Post-hoc pairwise comparison (Conover) furthermore revealed that for our elder participants loading duration and acceleration duration was shorter in LO than HO. Surprise trials (i.e. a mis-anticipation of the object's weight) led to an increase of the duration of the loading

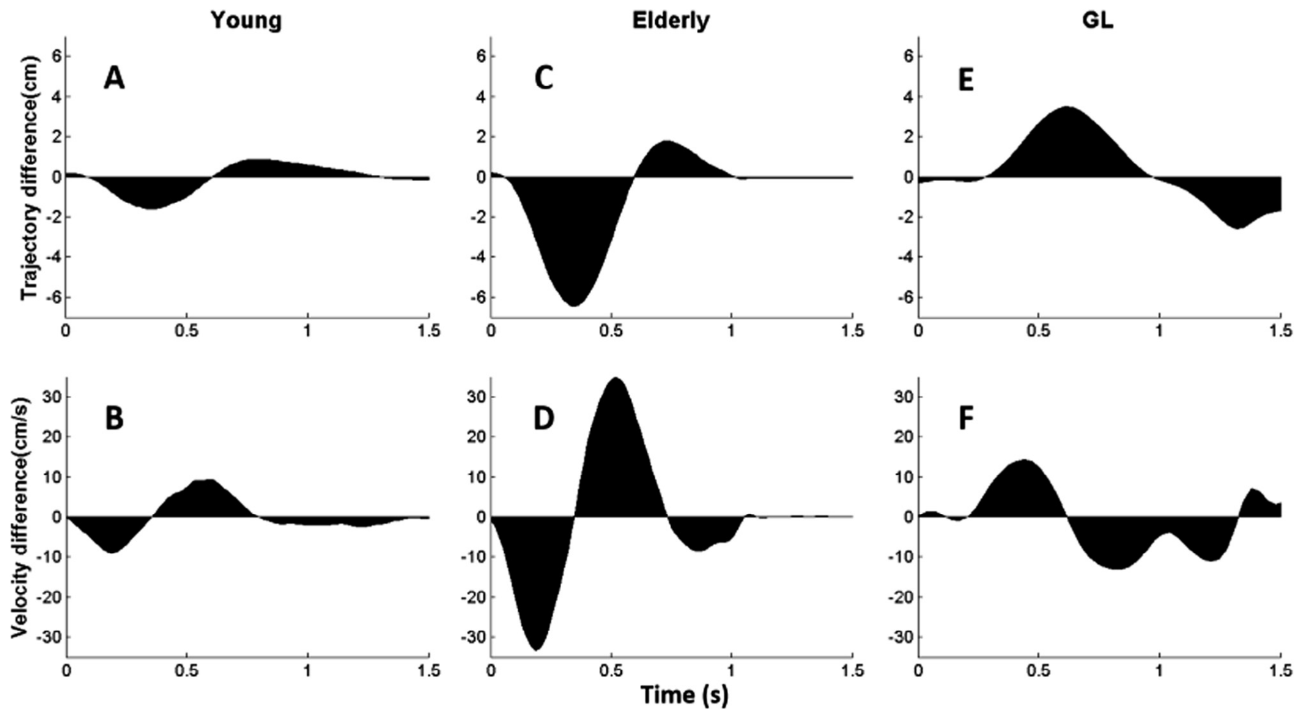

Fig. 7. Surprise effect upon kinematics. These graphics were obtained by subtracting the mean kinematic of HO condition from the mean kinematic of Surprise trials. For each group of participant (Plot A and B for young people, C and D for older adults and E and F for GL), height trajectory difference (Plots A, B and C) and velocity difference (plots B, D and F) are displayed. These plots highlight the effect of anticipation of weight upon the movement execution.

Table 2. Comparisons between HO, LO and surprise mean values for GL for different kinematic variables

GL's kinematic variables	Descriptive statistics		
	LO (N = 1, mean of 19 trials)	HO (N = 1, mean of 11 trials)	Surprise (N = 1 trial)
Reaction time (ms)	486.0	415.2	500
Reaching duration (ms)	719.3	730.3	666.7
Loading duration (ms)	1219.3	1415.2	1166.7
accelerated lifting duration (ms)	478.9	597.0	566.7
decelerated lifting duration (ms)	605.3	624.2	366.7
place duration (ms)	877.2	842.4	633.3
Velocity Peak (cm·s^{-1})	47.44	36.30	48.21
mean velocity (m·s^{-1})	9.10	8.57	11.26
maximal amplitude of object (cm)	23.01	21.86	22.50
symmetry ratio	0.82	0.99	1.55

and acceleration and a decrease of placing duration. Therefore, the symmetry ratio was also largely increased in the Surprise condition. *A contrario* there was no effect of surprise as compared with other heavy trials (Table 5, last column). Nonetheless, theses difference may nevertheless exist and could even be bigger compared to younger people, as observed in Fig. 7, even while the statistical test was non-significant, due to a higher variability in surprise condition in elder people.

GL

Comparison between HO and LO for GL by their mean values revealed that the HO condition led to a higher loading duration, an increased acceleration duration and a higher symmetry ratio (Table 2). Maximal amplitude of movement was, however, lower for HO than for LO. GL's Surprise trial induced a change in decelerated-lifting duration and in symmetry ratio as compared with LO trials. GL's Surprise trial also induced a change in decelerated-lifting duration and in mean velocity of the movement when it was compared with other heavy trials (Fig. 7).

Post-hoc power analysis

After performing G * Power analysis (Tables 3–5), the majority of outputs of d value are >1 and *power* >0.7. This signifies that the statistical tests used are valid despite the limitations concerning the number of participants.

DISCUSSION

Differences between groups

One of the most interesting results in this study was that majority of the durations of each movement phase and subsequently the overall movement duration were different in the three groups of participants (Fig. 2 and Table 3). GL was generally slower in executing the task compared to our other subjects while somewhat surprisingly our older subjects were faster than our younger participants. This latter observation is in contrast to other tasks using pointing movements involving either accuracy (Buchman et al., 2000) or time constraints (Ketcham et al., 2002; Welsh et al., 2007) where younger participants are generally faster than older people. In the present study we asked subjects to perform natural movement with the sole constraint of putting the object on the shelf. Since there was no constraint about speed or accuracy, this task falls within an ecological context and might explain the difference of results compared with other studies. In the study of Holt et al. (2013) for example, participants were required to transport different objects to targets at three different distances as fast as possible. Within this task, older people were slower and their peak velocities were not distributed constantly relative to the target distance. As proposed by a general speed-accuracy trade-off (Fitts, 1954), increasing movement speed decreases the final precision of movement when reaching the target. Interpreting the current results via Fitt's law, therefore, allows us to propose an explanation for the observed differences. While GL might employ a ''play-it-safe" strategy to reach the destination no matter the duration, elderly people might be more concerned about completing the task in a shorter period of time, with less concern for accuracy. Performers of the movements may find a compromise between moving quickly and reducing final spatial variability, which is time and energy consuming. In time constrained pointing movement, movements of older adults are generally characterized by a shorter primary sub-movement followed by larger and time consuming corrective actions (Lyons and Elliott, 1996; Ketcham et al., 2002). Hence they probably rely on feedback-based control to ensure reaching the final destination and avoiding positional errors. This suggests that older people performing our experiment may favor feed-forward control rather than online corrections as evidenced by the shortened acceleration phase duration during movement. At neurophysiological level, this interpretation is in accordance with the study of Klass et al. (2011) exploring the behavior of the H response and the long-latency component of the stretch reflex during different levels of maximal voluntary contraction (MVC) of the ankle. Interestingly, they demonstrated that although the H-reflex was less efficient for high levels of MVC, the long latency response was increased in older people with respect to younger. These results suggest that the modulation of afferent input diminishes with aging. Within this framework, it is plausible that elderly adults rely more on central mechanisms to compensate for a loss of peripheral control.

A common strategy employed in manual aiming tasks is to reach a ''fast but safe" zone under feed-forward control to a point as close as possible to the target and then accurately reach the point of destination using online feedback control (Desmurget and Grafton, 2000). The main difference between young and elderly would then be a difference in which the groups find their particular zones (Welsh et al., 2007). Within imposed constraints framework, it is then not surprising to observe that older subjects do not make more errors than younger ones (Goggin and Meeuwsen, 1992), but do so with a longer deceleration phase (Cooke et al., 1989; Darling et al., 1989) and lower peak velocity amplitudes (Cooke et al., 1989; Bellgrove et al., 1998). In contrast, in the present ecological task, our older participants were faster than younger people.

In the present study, the symmetry ratio (SR), whereas fairly close to unity in young subjects (Fig. 4 and Table 4), was greater than 1 in older subjects (Table 5), indicating that time spent accelerating was greater than the time spent decelerating. The symmetry of the velocity profile occurring during movement appears to be an invariant of the human motor system insensitive to a variety of variables (Todorov and Jordan, 1998) and appears to be a major criterion for human movement programing (Hogan, 1984). Despite this, the value of SR may differ depending on the viscous properties of the system, the ability to produce adequate agonist–antagonist patterns of muscle activities, the fatigue state of the system, movement velocity, weight and weight expectation (Jaric et al., 1998, 1999; Jaric, 2000). Concerning the last parameter, it was found that when an object was lifted with an expected weight, the value of the SR was always closer to 1 than when the object weight was unexpected. In our experiments SR showed a clear dependence on two factors: (1) actual load; and (2) expected load. Actual load was the same across all our subjects so we can accordingly suggest that the difference in SR values may rely on a different mode of control (Brown and Cooke, 1990; Cooke and Brown, 1990) depending on weight expectation.

Based on these observations and verified by the model developed here (Fig. 3), we have proposed that the strategy employed by younger people consists of underestimating voluntarily the weight of the lifted object, while older individuals may prefer overestimating it. The resemblance between experimental and prediction of the model tends to validate this hypothesis (Fig. 5 and Table 1). In this manner, elder people may favor the development of proactive forces (and thus a feedforward mechanism) to ensure the transportation of object whereas young people might rely more on feedback mechanisms. The predictions of the model using these parameters were consistent with these assumptions since they are close to the experimental measurements. Concerning the deafferented patient GL, we have assumed that she might deeply underestimate the weight of the object. Indeed, she showed substantially longer durations for all phases of movement than those of the other groups. Our interpretation is that she probably uses visual cues to trigger and control movement as she is completely deprived from somatosensory information. This process may engage longer latencies than other sensorimotor process that could be partially automated. She is also probably unable to update her feedforward internal models since information about object properties does not come from its mechanoreceptors but only from the visual consequence of her motor output. She therefore differs largely from other adults of the same age and her observed differences of movement might not be due to age.

Effect of weight and sequence on kinematics and dynamics

Previous authors have shown that in condition where intrinsic characteristics of objects are known, a linear relation between grip and load force is programed as a function of the expected mechanical characteristics of the object: expected heavier objects are lifted with a steeper increase of the grip- and load-force rate and by prolongation of the loading phase until lift-off (Johansson and Westling, 1988a, 1988b; Weir et al., 1991; Gentilucci, 2002; Brouwer et al., 2006; Eastough and Edwards, 2007). The duration of the loading phase increases even when the heavier weight is unexpected, due to the progressive and discontinuous build up of a sufficient load force to overcome gravity (Westling and Johansson, 1984; Johansson and Westling, 1988a). In our experiment, all subjects modified their behavior when the object gained weight; a heavy weight requires more time to be lifted as compared to a lighter weight. This is in favor of the hypothesis of an anticipation of the weight of the object to pre-program at least partially the movement.

In the case of lifting movements in a blocked condition, the mass can be anticipated according to previous trials because subjects can rely on their sensorimotor memory (Nowak and Hermsdörfer, 2003). It is known that repetition allows one to guess the extrinsic and intrinsic properties of an object from trial to trial (Nowak and Hermsdörfer, 2003). When playing with visual appearance of an object like changing the size to produce a size-weight illusion, one can also see consistent effects of mass prediction on lifting movement (Meulenbroek et al., 2007). Introducing a different weight of the object without, however, changing its visual appearance led subjects to an erroneous guess of the intrinsic property. Interestingly, our younger subjects and GL displayed a pronounced effect of surprise, suggesting that they all rely in the anticipation of weight of object based upon their recent sensorimotor experiment. In contrast, statistics computed on elder adults didn't show a significant difference between surprise and other heavy trials. However, when comparing the mean difference between these two conditions, it seemed that, in contrast to our younger subjects, heavy trials are indeed well different from surprise trials (Fig. 7) and that effect of surprise was even larger for older than younger subjects. In the Surprise condition, there was a tendency for older people to express a weaker velocity peak (Fig. 6 and Table 5), reflecting the importance of anticipation in the movement programing and regulation in this population. Despite this observable phenomenon, statistical analysis of surprise in the older group was not significant. The explanation is that the variance of kinematic measures among heavy, surprise movement was quite large in our older subjects. As the statistical methods take into account the overall distribution of the different populations, it is therefore not surprising to find no statistical significance between surprise and other heavy trials. Relying on this fact, this could imply that older people rely more heavily on *a priori* estimation of object properties to execute their movement and are thus more exposed to variability depending on the actual weight of the object. Thus and again, it seems that the strategy employed by older adults depends on feedforward mechanism in which environmental parameters anticipation are crucial to properly execute the movement.

Building motor strategy with available sensory information

It has been shown that the intrinsic property of mass of an object is extracted from cutaneous information during the grasping and loading phase (Johansson and Westling, 1984) (Johansson et al., 1992a) or by proprioceptive information arising from upper arm and hand muscles at the time of lifting (Jami, 1992; Nichols, 2002). When these afferent signals are absent, as in the case of GL, humans tend to rely on other available sources of information. In a weight discrimination task, Fleury et al. (1995) found that GL's performance depended mainly on visual information. By removing vision, errors in movement direction and amplitude were found when pointing to target placed at different locations (Ghez et al., 1990). GL is also known to possess an efficient memory control of voluntary muscle contractions (Teasdale et al., 1993; Nicolas et al., 2005) and possibly, she uses it to calibrate her hand trajectory. She could also use vestibular afferences in accordance with work done by Fleury et al. (1995) who found that these inputs are quite important to appreciate the weight of a lifted object in GL. Nevertheless, GL, like healthy subjects, was entirely able to perform the task and displayed stable kinematics in the late part of the movement. Her lack of proprioceptive afferent signals does not allow her to predict the mass of the object in the beginning of trials, so, she behaved in the same way in both HO and LO conditions and consequently the movement produced is quite different according to gravity forces acting on the object as revealed by kinematics and modeling of the task. Indeed, in contrast to our younger and older participants, GL attained slightly higher movement amplitudes for LO than for HO trials. (Fig. 6). One might conclude that she produces a weaker feedforward force to overcome gravity thus explaining longer delays in the different phases and slower movement: she might care about achieving the goal, which she always managed to do, rather than executing her movements under homogeneity (i.e. reducing variability among movements) and performance (i.e. completing the task in a short period of time) criteria. Altogether, the characteristics of GL's performance suggest *a contrario* that feedback control plays a role in adaptation of effort to change of weight.

Motor modifications with aging

Numerous studies have shown that neuronal changes arise when advancing in age that are directly and indirectly linked to motor control. This includes morphological changes (Davatzikos and Resnick, 2002; Raz et al., 2005) and biochemical alterations (Garnett et al., 1983; Gottfries, 1990; Gould and Bickford, 1996; Kaasinen and Rinne, 2002). The sensory system is also affected by loss of cutaneous (Jones and Lederman, 2006), proprioceptive (Hurley et al., 1998), vestibular (Zalewski, 2015) and visual sensitivity (Owsley, 2011). Additionally, elder people may also be confronted by structural and functional modifications of the peripheral motor system including reduction of muscular mass (Roos et al., 1999) associated with a reduction of the muscular fiber population (Lexell et al., 1988) and reorganization of motor units (Doherty et al., 1993). All of these modifications can affect motor control output. Indeed, it has been reported that variability of movement increases with advancing age (Contreras-Vidal et al., 1998). Movement is also slowed down (Bennett and Castiello, 1994; Carnahan et al., 1998) and postural control is more demanding (Woollacott and Tang, 1997)(Maki et al., 1990). Older subject also experience difficulty in modulating force output (Kinoshita and Francis, 1996) and coordination ((Seidler et al., 2002) (for a review see Ketcham et al. (2002)). In addition, numerous studies have documented a functional difference of aged brain with respect to motor control (Calautti et al., 2001; Mattay et al., 2002; Ward and Frackowiak, 2003; Heuninckx et al., 2005, 2008). Based on this body of evidence, several authors have argued that the mode of control in the elderly is largely dependent on the continuous refining of visual information about target location (Haaland et al., 1993; Sarlegna, 2006). That would lead to behavior close to what we observed for GL. On the contrary, in the present experiment the kinematic results of older participants were quite different from both younger participants and GL, suggesting that older people may prefer to use feedforward mechanisms rather than feedback processes to control their movement. This can be viewed as an alternative strategy, which has already been proposed to compensate for the loss of structural and functional properties of nervous system when advancing in age (Li and Lindenberger, 2002; Heuninckx et al., 2008; Seidler et al., 2010). The observed kinematics of quicker movement may also be interpreted in the 'dynamicist' view defended by Engel et al. (2001). As the classical bottom-up process of the perceived object is realized by hierarchical neuronal processing primarily based on peripheral sensory information, there is a high probability that it is perturbed with age. In contrast, the top–down process may use large-scale dynamics in order to enslave local processing influenced by sensory input to trigger a specific acting strategy. We may suggest that a top-down process, more based on an expectation-driven processing, could be enriched over the lifespan and preferably used by older people.

CONCLUSION

In this study we have investigated how younger and older people, and one deafferented individual (GL), lift objects with different weights but similar appearance in an ecological context (no constraints upon achievement duration). From the kinematics measured of the hand and object, we have observed that elderly people moved faster than younger people in the transportation of objects. In contrast, GL was slower and produced lower trajectories than young people. We postulate from this observation that older people might rely more on their internal model to achieve the task by producing sufficient or even greater feedforward forces than necessary to lift the object, whereas younger people might produce weaker feedforward forces, thus favoring a feedback control mode when operating with uncertain object properties. Despite her age, which was comparable to the elderly group of subjects in this study, GL accomplished the task much more slowly. According to a model that we developed to simulate the forces that act together to produce the desired trajectory, and based on some simple assumptions about the subject's motor plan, we propose that older subjects may produce their lifting movements with an overestimation of the object's weight, compared to the tendency for underestimation by younger participants. Because of her deficit, GL seems to strongly underestimate the weight of object and seems to rely on different mechanisms of feedback, such as vision or vestibular afferences. To conclude, one might say that aging leads to usage of alternative strategies to accomplish daily-life activities.

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APPENDIX A.

Table 3. Statistical and analytical comparisons between young, elderly and GL subjects for different kinematic variables. The first, second columns show mean ± standard deviation obtained from the mean of each participants in young and older people respectively (mean of all trials except surprise). The third column shows mean values of GL participant (mean of all trials except surprise). The fourth column shows statistical difference between the young and elderly for each kinematic variable using Mann–Whitney *U* test (** when $p < 0.01$, * when $p < 0.05$). It also contain the value of the effect size (d) and the power computed using an appropriate post hoc power test with G * Power software (Faul et al., 2007). In the last two columns the mean value of GL was compared with the mean ± 1.96 * SD in the young group (column 5) and elderly group (column 6). When the calculated interval did not contain the GL kinematic value, we noted the variable as analytically significant (marked with a ≠ symbol)

Kinematic Variables	Descriptive Statistics			Statistical comparison (Mann–Whitney *U* test)	Analytical comparisons	
	Younger (N = 7)	Older (N = 7)	GL (N = 1)	Younger vs. Older	Younger vs. GL	Older vs. GL
Reaction time (ms)	335.1 ± 83.4	307.5 ± 55.9	460.0	U = 18, p = 0.831 d = 1.1389 Power = 0.4784	∈ [171.6 498.6]	∉ [197.9 417.1] ≠
Reaching duration (ms)	452.0 ± 92.1	313.7 ± 66.6	723.3	U = 6, p = 0.018* d = 1.5871 Power = 0.7550	∉ [271.5 632.5] ≠	∉ [183.2 444.2] ≠
Grasping duration (ms)	567.4 ± 162.2	372.0 ± 101.9	1291.1	U = 6, p = 0.018* d = 1.4857 Power = 0.6992	∉ [249.5 885.3] ≠	∉ [172.3 571.7] ≠
accelerated lifting duration (ms)	351.9 ± 70.0	291.1 ± 24.2	522.2	U = 9, p = 0.048* d = 1.3648 Power = 0.6261	∉ [214.7 489.1] ≠	∉ [243.7 338.5] ≠
decelerated lifting duration (ms)	399.7 ± 147.1	264.8 ± 42.5	612.2	U = 4, p = 0.009** d = 1.3320 Power = 0.6244	∈ [111.4 688.0]	∉ [181.5 348.1] ≠
place duration (ms)	611.0 ± 141.7	476.5 ± 101.7	864.4	U = 10, p = 0.064 d = 1.3622 Power = 0.6243	∈ [333.3 888.7]	∉ [277.2 675.8] ≠
Velocity Peak ($cm \cdot s^{-1}$)	60.36 ± 15.00	83.38 ± 11.67	43.36	U = 5, p = 0.013* d = 1.7135 Power = 0.9021	∈ [30.96 89.76]	∉ [60.51 106.25] ≠
mean velocity ($m \cdot s^{-1}$)	14.14 ± 3.10	17.89 ± 1.97	8.91	U = 7, p = 0.025* d = 0.8675 Power = 0.3065	∈ [8.06 20.22]	∉ [14.03 21.75] ≠
maximal amplitude of object (cm)	21.78 ± 0.72	22.37 ± 1.25	22.59	U = 16, p = 0.277 d = 1.3293 Power = 0.6035	∈ [20.37 23.19]	∈ [19.92 24.82]
symmetry ratio	0.95 ± 0.08	1.13 ± 0.12	0.88	U = 3, p = 0.006** d = 1.0827 Power = 0.4413	∈ [0.79 1.11]	∉ [0.89 1.37] ≠

Table 4. Statistical comparisons between HO, LO and surprise trials for younger subjects in different kinematic variables. The first, second and third columns show mean ± standard deviation values in LO, HO and surprise respectively obtained from the mean values of each participants. The fourth column shows statistical possible differences between the three conditions in tested kinematic variables using Friedman ANOVA. Results were obtained by comparing the mean results of each subject. When p value < 0.05, a statistical post hoc (Conover) was used to reveal which conditions differ. Significant variables are marked as ** when $p < 0.01$ and * when $p < 0.05$. When pairwise comparisons tests were used a post hoc power analysis using G*Power (Faul et al., 2007) was used to reveal the effect size (d) of the two different conditions as well as the power of the statistical used test

Young Kinematic variables	Descriptive Statistics			Friedman ANOVA after Iman and Davenport (1980)	Pairwise Comparisons (Conover)		
	LO (N = 7)	HO (N = 7)	Surprise (N = 7)		LO vs. HO	LO vs. Surprise	HO vs. Surprise
Reaction time (ms)	340.8 ± 91.6	325.5 ± 73.8	314.3 ± 61.2	$T_2(F)$ = 0.1111 p = 0.8956			
Reaching duration (ms)	448.6 ± 93.0	457.5 ± 90.5	600.0 ± 291.1	$T_2(F)$ = 0.0857 p = 0.9183			
Loading duration (ms)	507.0 ± 129.3	667.0 ± 213.6	735.7 ± 455.4	$T_2(F)$ = 10.92 p = 0.0014**	p = 0.0005** d = 1.8283 power = 0.9999	p = 0.0046** d = 0.5548 power = 0.4849	p = 0.2805 d = 0.1822 power = 0.0970

Table 4 (*continued*)

Young Kinematic variables	Descriptive Statistics			Friedman ANOVA after Iman and Davenport (1980)	Pairwise Comparisons (Conover)		
	LO ($N = 7$)	HO ($N = 7$)	Surprise ($N = 7$)		LO vs. HO	LO vs. Surprise	HO vs. Surprise
accelerated lifting duration (ms)	318.9 ± 56.1	406.4 ± 108.2	457.1 ± 118.2	$T_2(F) = 9$ $p = 0.0031^{**}$	$p = 0.0522$ $d = 1.0222$ power = 0.9418	$p = 0.0008^{**}$ $d = 1.0522$ power = 0.9528	$p = 0.0522$ $d = 0.4813$ power = 0.3853
decelerated lifting duration (ms)	409.4 ± 165.4	384.5 ± 122.0	357.1 ± 73.8	$T_2(F) = 0.1111$ $p = 0.8956$			
place duration (ms)	600.8 ± 132.1	627.2 ± 169.1	645.2 ± 150.6	$T_2(F) = 0.1111$ $p = 0.8956$			
Velocity Peak ($cm{\cdot}s^{-1}$)	61.75 ± 15.47	57.97 ± 14.16	54.70 ± 11.07	$T_2(F) = 1.615385$ $p = 0.2338$			
mean velocity ($m{\cdot}s^{-1}$)	14.43 ± 3.20	13.64 ± 3.01	12.79 ± 2.55	$T_2(F) = 0.4667$ $p = 0.6365$			
maximal amplitude of object (cm)	21.58 ± 0.69	22.15 ± 0.83	22.39 ± 0.83	$T_2(F) =$ infinity $p < 0.0001^{**}$	$p < 0.0001^{**}$ $d = 1.4383$ power = 0.9986	$p < 0.0001^{**}$ $d = 1.1719$ power = 0.9814	$p < 0.0001^{**}$ $d = 0.2479$ power = 0.1382
symmetry ratio	0.85 ± 0.15	1.11 ± 0.14	1.32 ± 0.38	$T_2(F) = 3.4186$ $p = 0.0618$			

Table 5. Statistical comparisons between HO, LO and surprise trials in older people in different kinematic variables. The first, second and third columns show mean ± standard deviation values in LO, HO and surprise respectively obtained from the mean values of each participants. Fourth column show statistical possible difference between the three conditions in tested kinematic variables using Friedman Anova test. Results were obtained by comparing the mean results of each subject. When p value < 0.05, a statistical post hoc (Conover) was used to reveal which conditions differ. Significant variables are bolded and marked as ** when $p < 0.01$ and * when $p < 0.05$. When pairwise comparisons tests were used a post hoc power analysis using G * Power (Faul et al., 2007) was used to reveal the effect size (d) of the two different conditions as well as the power of the statistical used test

Elderly Kinematic variables	Descriptive statistics			Friedman ANOVA after Iman and Davenport (1980)	Pairwise Comparison (Conover)		
	LO ($N = 7$)	HO ($N = 7$)	Surprise ($N = 7$)		LO vs. HO	LO vs. Surprise	HO vs. Surprise
Reaction time (ms)	301.4 ± 47.9	317.0 ± 69.3	263.9 ± 32.5	$T_2(F) = 2.909091$ $p = 0.0933$			
Reaching duration (ms)	317.6 ± 68.8	307.4 ± 65.0	316.7 ± 50.9	$T_2(F) = 0.146341$ $p = 0.8654$			
Loading duration (ms)	336.8 ± 99.9	429.8 ± 111.6	400.0 ± 160.2	$T_2(F) = 8$ $p = 0.0062^{**}$	$p = 0.0026^{**}$ $d = 1.7536$ power = 0.9999	$p = 0.0106^{*}$ $d = 0.3526$ power = 0.2314	$p = 0.4643$ $d = 0.1812$ power = 0.0964
accelerated lifting duration (ms)	268.8 ± 32.2	328.4 ± 12.2	475.0 ± 143.0	$T_2(F) = 8$ $p = 0.0062^{**}$	$p = 0.0106^{*}$ $d = 2.5074$ power = 1	$p = 0.0026^{**}$ $d = 1.4067$ power = 0.9980	$p = 0.4643$ $d = 0.9909$ power = 0.9282
decelerated lifting duration (ms)	260.9 ± 38.0	271.2 ± 50.8	244.4 ± 34.2	$T_2(F) = 0.914634$ $p = 0.4269$			
place duration (ms)	503.1 ± 114.4	432.9 ± 89.1	394.4 ± 50.6	$T_2(F) = 4.5$ $p = 0.0348^{*}$	$p = 0.0731$ $d = 1.3564$ power = 0.9967	$p = 0.0122^{*}$ $d = 1.0302$ power = 0.9449	$p = 0.3455$ $d = 0.4311$ power = 0.3212
Velocity Peak ($cm{\cdot}s^{-1}$)	86.99 ± 12.50	77.45 ± 10.62	68.00 ± 15.88	$T_2(F) = 3.8$ $p = 0.0527$			
mean velocity ($m{\cdot}s^{-1}$)	17.94 ± 2.08	17.80 ± 1.94	16.33 ± 1.03	$T_2(F) = 1$ $p = 0.3966$			
maximal amplitude of object (cm)	22.34 ± 1.42	22.45 ± 1.10	22.69 ± 2.14	$T_2(F) = 1.35$ $p = 0.2959$			
symmetry ratio	1.05 ± 0.09	1.27 ± 0.20	1.96 ± 0.58	$T_2(F) = 6.25$ $p = 0.0138^{*}$	$p = 0.1025$ $d = 1.4101$ power = 0.9981	$p = 0.0041^{**}$ $d = 1.4354$ power = 0.9986	$p = 0.1025$ $d = 1.0791$ power = 0.9612

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