Motor adaptation capacity as a function of age in carrying out a repetitive assembly task at imposed work paces

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Abstract

The working population is getting older. Workers must adapt to changing conditions to respond to the efforts required by the tasks they have to perform. In this laboratory-based study, we investigated the capacities of motor adaptation as a function of age and work pace. Two phases were identified in the task performed: a collection phase, involving dominant use of the lower limbs; and an assembly phase, involving bi-manual motor skills. Results showed that senior workers were mainly limited during the collection phase, whereas they had less difficulty completing the assembly phase. However, senior workers did increase the vertical force applied while assembling parts, whatever the work pace. In younger and middle-aged subjects, vertical force was increased only for the faster pace. Older workers could adapt to perform repetitive tasks under different time constraints, but adaptation required greater effort than for younger workers. These results point towards a higher risk of developing musculoskeletal disorders among seniors.

Keywords: age, work pace, motor adaptation.

Highlights

- Aging and work pace are two factors affecting workers' motor adaptations used to perform the required work.
- All three age groups of workers were able to adapt their output to the two imposed work paces.
- Motor adaptation was more difficult to achieve for older workers when movement involved more the lower limbs in the task.

Introduction

As in most European countries, the working population in France is ageing. Two facts have led older workers to remain at work for longer. First, the current sociodemographic situation shows that the segment of population between 55 and 65 years of age is growing due to the high birth rate from 1945 to 1974. And second, reforms to public policies related to funding for retirement pensions have postponed the age of retirement (DARES 2011).

However, a person’s health status, including physiological and psychological systems, changes as age progresses (Seitsamo and Klockars 1997, Kowalski-Trakofler et al. 2005). For example, in terms of functional capacities, the knee extensors have been observed to lose strength in seniors and tendon extensive properties is known to decrease with age (Kubo et al. 2007, Viitasalo et al. 1985). Older employees also produce less muscular force than younger ones (Mathiowetz et al. 1985, De Zwart et al. 1995, Broersen et al 1996, Reilly et al. 1997, Ilmarinen 1997, Robertson and Tracy 1998, Ilmarinen 2001, Macaluso and De Vito 2004). These differences could be due to several factors: sarcopenia, changes in excitation-contraction coupling, modifications to the tendons and bones, and changes in nerve control (Macaluso and De Vito 2004, Narici and Maffulli 2010). These changes in force production with age nonetheless depend on the group of muscles analysed. Thus, the strength of the lower limbs appears to be more affected by age than that of the upper limbs (Viitasalo et al. 1985, Lynch et al. 1999, Narici and Maffulli 2010). This difference is linked to preferential atrophy of the lower limb muscles (Doherty 2003, Janssen et al. 2000, Mascaluso and De Vito 2004, Narici and Maffulli, 2010). In the long-term, this atrophy may cause older people to adopt a sedentary lifestyle. The upper limbs are more preserved as a great proportion of daily manual activities involves these muscle groups (Kornatz et al. 2005, Narici and Maffulli 2010).

These physiological data illustrate older workers the potential embrittlement. It can explain why they are more likely to develop musculoskeletal disorders than younger workers (Kim et al. 2010). In addition, although most older employees still seem fit enough to continue their work, the fact that they require longer to recover after working and sustained effort cannot be ignored (Kiss et al. 2008, Cote et al 2014). Moreover, the burden of years of work can be seen in how functional capacities evolve. Indeed, several studies have shown a strong correlation between the increase in age-related mobility problems and deterioration of hip and knee joints due to occupational exposure (Maetzel et al. 1997, Rossignol et al. 2005, Werner et al. 2011). This general trend for fragility in older workers must nonetheless be moderated by the itinerary of the individual concerned. This life course brings into play many independent factors such as lifestyle, education, practicing physical exercises, socioeconomic status, stress, and so on.

However, age is not the only factor that should be taken into account when analysing work-related efforts. For example, it is just as important to evaluate whether the physical demands required by the workplace do not exceed the employee’s physical capacities (Okunribido et al. 2011). The influence of the physical load, in combination or not with age-related effects, may be revealed by the employee's motor adaptation capacities when performing tasks. This adaptation therefore requires a modification of the motor resultant represented by voluntary movement. Indeed, a number of questions must be solved by the central nervous system to compute a voluntary movement. The movement should appropriately meet the expected goal and the context in which it must be accomplished. The notion of internal models emerged as a possible system to mimic the hypothetical paths that the brain uses to determine and produce the appropriate move (Wolpert et al. 1998). Two types of internal model can be distinguished: the inverse model calculates the appropriate command to put the body into the desired articular configuration; and the forward model, which predicts the body's reactions to the command given via a system of efferent copies of motor commands (Miall and Wolpert 1996, Wolpert and Kawato 1998, Todorov 2004). The decision to perform a movement is made based on a compromise between the cost and the risk after taking in a large amount of both internal and external sensorial and cognitive information (Wolpert and Landy 2012).

When performing work on an assembly line, the motor adaptation required to correctly complete a task is continually present. Performing a repetitive movement to meet production objectives despite the environmental hazards at the moment of execution represents an additional constraint for all workers (Kilbom 1994). However, the time constraint often involved in repetitive work becomes particularly penalising for older employees (Derriennic et al. 1990, Molinié 2003, Volkoff et al. 2010). Xu et al. (2014) also observed that female workers of different ages were capable of working at a set pace with no difference in timing of hand movements. These authors assumed that older participants had to work closer to their physical limits. Indeed, compared to younger workers, older workers showed more effort in adaptation to maintain the same motion strategies in response to muscle fatigue (Qin et al., 2014a, 2014b). Moreover, time constraints can limit intra-individual variability in the motor responses observed, even for spatially and temporally constraining tasks (Madeleine et al. 2003, Mathiassen et al. 2004, Möller et al. 2004, Madeleine et al. 2008, Dempsey et al. 2010). Nevertheless, this variability could be beneficial in protecting the health of ageing workers.

In this paper, we present the results of a controlled laboratory study in which three groups of subjects of different ages performed a standardised task at two predetermined paces. The objective was to assess the effect of age on the motor adaptation capacities of employees to a repetitive work performed at two different imposed paces. Two kinds of adaptation were analysed during the repetitive task performed. One focused more on adaptations to whole-body movement, whereas the other focused more on adaptations to upper limb movements. Our hypothesis was that older workers can adapt, but that adaptations become more difficult when pace increases. Moreover, the difficulty adapting should be more apparent for whole-body movement than for upper limb movement.

Method

Participants

Sixty-five right-handed men voluntarily agreed to participate in the experiment. Subjects were recruited based on two criteria. First, the subjects had to fall into one of the following three age groups: junior (J), 30 to 35 years old; middle-aged (M), 45 to 50 years old, and senior (S), 60 to 65 years old. The characteristics of the three age groups are presented in Table 1. Secondly, all subjects had to have worked or be still working in what is considered a "physically demanding" job to ensure homogenous evolution of functional capacities. All participants provided a complete description of their work activities throughout their professional lives. In all cases, during a large part of their careers, they either had to carry loads, or work in awkward postures performing construction or carpentry work, or working in a mechanical workshop. Participants were recruited either through a temporary employment agency or responded to small ads published in local papers. Participant's functional capacities were assessed before the experiment through flexibility tests, dexterity (based on the Purdue pegboard test (Desrosier et al. 1995)), speed of upper limb movement, and analysis of the muscular force of the upper and lower limbs. At the end of the assessment, subjects were familiarised with the task they would have to perform during the experiment by completing 10 assemblies as fast as possible. All subjects gave their free and informed consent for participation in this study, the protocol for which was approved by the Consultative Committee for the Protection of Subjects in Biomedical Research (institutional ethics committee).

Procedure

Subjects were asked to perform a repetitive mounting task during two 20-minute work sessions, at two different work paces. The conditions in which the mounting was performed were similar to those found on an assembly line. Three activity phases were identified in each mounting cycle (figure 1a):

1- A moving phase: this phase involving movement from the base part dispenser to the assembly station work at the beginning of the mounting cycle, and from the assembly station to the dispenser at the end of the cycle.

2- A collecting phase: during this phase component parts – a handle and two nuts – were collected. Parts were stored under the assembly table. This phase was a motor task involving more predominantly the lower limbs.

3- An assembly phase: during this phase a handle was fixed to a base by screwing two nuts onto two threaded rods (figure 1b). This phase was performed on the assembly table. It corresponded to a motor task mainly involving the upper limbs.

Subjects were instructed to collect the exact number of component parts (one handle and two screws) for each of the mounting cycles and not to take parts in advance for subsequent tasks. No instructions were given as to how to proceed when collecting or assembling the component parts, it was simply specified that the assembly had to be entirely completed on the assembly table. The assembly could not be completed during the journey back to the dispenser. The base dispenser and assembly table were spaced 3 m apart. The height of the assembly table was adjusted based on each subject's anthropometric proportions.

Of the three activity phases identified above, only collection and assembly were quantitatively analysed. The starts and ends of these two phases were determined using identifiable events on displacements of the anteroposterior and lateral "sacrum" joint centre (figure 2). The start of the collection phase was marked by triggering vertical descent of the sacrum. This moment was taken as zero for the time analysis, allowing synchronisation of all the mounting cycles to allow data comparison between trials and between subjects. The collection phase was further divided into three consecutive periods: i) flexion of the subject to reach for separate parts, identified by the vertical descent of the sacrum; ii) collection of the parts from their respective reservoirs; iii) extension of the subject as they returned to a standing position. The collection phase was considered completed when the sacrum returned to a position close to its initial vertical position, before stabilising at a plateau level. The assembly phase began at this same moment and ended when the subject withdrew the fully assembled component from the assembly table and began their half turn to return towards the supply site. This event was characterised by a rightwards (positive peak in figure 2) or leftwards lateral displacement of the sacrum, depending on whether the subject pivoted on their right or left foot.

The two work sessions were performed on two successive mornings, one for each prescribed work pace. The pace of work was defined as “comfortable” or “rapid”. The comfortable pace required completion of one mounting cycle every 25 s, i.e., a maximum of 49 assemblies to be performed over 20 minutes. The rapid pace required one mounting cycle every 20 s, i.e., a maximum of 60 assemblies to be completed over 20 minutes. To prevent any order effect, the order in which the two work paces were performed was assigned randomly ensuring that, for each age class, as many subjects started with the comfortable work pace as with the rapid work pace. When the instructions were presented, subjects were made particularly aware of the importance of maintaining the pace of work. If they failed to comply with this condition, they were reminded of it during the experiment. The rate was imposed by the base dispenser. The experiment was designed to provide the subject with real-time information on their progress with respect to the prescribed work pace, and to allow them to correct it if necessary. The base dispenser was divided into four identifiable parts (figure 1a). This setup was used to verify whether the subject kept to the work pace as they deposited the assembled part into the same region of the dispenser after it had performed a full rotation. It was also used to calculate any delay, either caught up or accumulated, if the subject was unable to maintain the pace. The comfortable work pace was defined based on pre-tests involving ten subjects aged 22 to 55 who had to perform as many mounting cycles as possible in 20 minutes. The average time observed was consistent with the 22 s per assembly cycle determined by “Method Time Measurement” (MTM). MTM is an engineering tool used to calculate cycle times for industrial assembly tasks. Therefore, the comfortable work pace was defined as 25 s, and the rapid rate as 20 s, which corresponds to a 20% increase in pace.

Apparatus

For each mounting cycle, the forces and moments exerted on the floor were recorded using an AMTI® force plate, and those exerted on the assembly table were recorded using an ATI® sensor positioned under the assembly table. All the dynamic signals were recorded at a frequency of 200 Hz. The displacements of 37 passive markers - placed on subjects in relation to anatomical landmarks - were simultaneously measured at a frequency of 50 Hz using a Vicon 460® optoelectronic system. To perform the kinematic analysis, 14 body segments (2 feet, 2 legs, 2 thighs, the pelvis, the abdomen, the thorax, 2 arms, 2 forearms and the head) and the joint centres corresponding to the links between these different segments were reconstructed using Hanavan’s (1964) biomechanical model of inverse dynamics. This model was developed using recordings of marker displacements combined with 67 anthropometric measurements on subjects and dynamic measurements (force plates placed on the floor and under the table). The model was used to calculate the Euler angles of flexion-extension for the ankle, knee, hip and shoulder joints, as well as the abduction-adduction of the hips and shoulders. These angles were calculated according to the recommendations made by the International Society of Biomechanics (Wu & Cavanagh, 1995, Wu et al., 2002). For each subject, the angles analysed were determined by calculating the difference between the angle measured at the instant studied (collection or assembly phase) and that measured on a reference posture. The reference posture corresponded to subjects standing with their feet aligned vertically below the hips, with a straight back. Upper limbs were aligned along the body with the palms of the hands facing the outer thighs. The reference posture was recorded before starting each work session. Ankle flexion increase corresponded to inclination of the anterior face of the leg towards the instep. Knee flexion increase was defined as closing in of the posterior face of the leg towards the posterior face of the thigh. Hip flexion increase corresponded to inclination of the anterior face of the trunk towards the anterior face of the thigh. Shoulder flexion increase was defined as raising the anterior part of the arm in the sagittal plane. For hip and shoulder joints, abduction increase corresponded to displacement of the member outside the median plane of the body, in the frontal plane.

Statistical analysis

Variables were recorded during each mounting cycle performed by each subject at the two work paces. The delay was compared to the prescribed time to determine the subject's capacity to adapt to the work pace. The duration of both collection and assembly phases was measured. The amplitude, speed and lower limb angles were measured for flexion and extension movements performed during the collection phase. The upper limb angles and vertical force were measured during the assembly phase. Statistical analysis of each of these variables was based on multi-level linear models fitted using maximum likelihood, to analyse three random effects: between-subject, between-subject x work pace, and within subject. The following factors were also analysed to determine their influence: age group, pace, and their interactions; they were considered fixed effects. The approximate normal distribution of random effects was verified on histograms of the residuals. Based on these descriptions, log transformation was performed on some variables. The parameters estimated by this model were: the variance of three random effects, the effect of age group during the tests at "comfortable" pace, the effect of work pace (rapid vs. comfortable) in the youngest age group and the two interaction parameters. The interaction parameters represented the difference in effect due to work pace in the middle-aged vs. junior and in the older vs. junior groups. The threshold for statistical significance was set at $p<0.05$.

The first analysis explored whether senior group can adapt to the prescribed work pace. For each pace, and for all subjects in each age group, the mean values of the time spent to complete a full mounting cycle according to the mounting cycle number were calculated. The second block of analyses explored variables characterising the collection phase (vertical displacement and velocity of the sacrum joint, flexion and abduction angles for knee and hip joints) for each age group and pace, and their interactions. The third block of analyses explored the variables characterising the assembly phase (vertical force exerted on the assembly table and flexion and abduction angles for the shoulder joints) for each age group and pace, and their interactions.

Results

Keeping up with the prescribed work pace

At the comfortable pace, 5 junior, 8 middle-aged and 9 senior subjects temporarily lagged behind the prescribed pace. However, whatever the age group, the delays were always wholly caught up before the end of the work session. The other subjects maintained the pace continually without loss of rhythm (figure 3, top).

At the rapid pace, only 3 young and 4 middle-aged subjects were able to maintain the work pace without lagging. Occasional, but compensated, delays were recorded for 15 young, 12 middle-aged and 9 seniors subjects. In contrast, 2 young, 5 middle-aged and 9 older subjects fell behind at the beginning of the session but were able to stabilise the work rhythm at the pace required latter. Juniors and middle-aged subjects acquired and maintained the work rhythm after less than 5 mounting cycles, while seniors subjects needed at least fifteen parts assembled to get there. One middle-aged and 5 seniors subjects continually fell behind during the full 20-minute work session (figure 3, bottom).

Performing the mounting cycle

Collection phase

Two very distinct groups of measurements were observed when inspecting the model residuals for both downward vertical sacrum displacement and sacrum velocity (figure 4). For 88% of the data, downward sacrum amplitude of greater than 0.25 m was observed, with knee angular flexion amplitudes exceeding 70°, and flexion speed greater than 0.3 $m.s^{-1}$. For the remaining

12% of data, downward sacrum amplitude was less than 0.25 m, knee flexion amplitudes were lower than 70°, and flexion speed lower than 0.3 $m.s^{-1}$. This second data group, with little or no knee flexion was composed of: 23% young, 11% middle-aged and 66% senior subjects. No differences between the two groups were observed in terms of weight, height, or back flexibility measurements. Thus, the two groups clearly identify two ways in which component parts can be collected. Consequently, for the collection phase, it was decided to restrict analysis to the replicates in which the knees were flexed; this did not result in exclusion of any individual subjects, since none of them performed this type of collection throughout the period of their work session.

Table 2 presents the statistical analysis of the variables measured during the collection phase. The first six columns show the means (standard deviation) calculated over all trials for all subjects grouped by age group and work pace. The latest three columns present the statistical significance of the two main effects (age group and pace, respectively) and their interaction. No effect was observed for hip flexion. However, significant interactions were identified for all the other variables for the different age groups, indicating that the increase in pace had a significant effect on these parameters. These results show that, at both work paces, seniors subjects were significantly slower and showed less lower limb flexion than the two other groups. Also, all age groups showed a decrease in collection time with the increase in pace even though the effect was less pronounced for senior subjects than for other groups. No significant variation in values between the beginning and the end of the 20-minute work was observed for any of the variables at either pace (data not shown).

Assembly phase

Data from the assembly phase were homogeneously distributed. Therefore, no data were excluded from the statistical processing for this phase. Table 3 shows the results of the statistical analysis for the same variables as measured in the collection phase; the structure is the same as in Table 2. No interaction was observed for the duration of assembly or the vertical force applied on the table during assembly. In addition, no significant difference was observed for the duration of assembly for the different age groups at either of the work paces studied. Thus, for all groups, the duration of assembly was significantly shorter when the pace increased. In contrast, differences were observed for the vertical force applied to the assembly table. This force increased significantly with advancing age and as the work pace increase. Increasing the pace led to a similar increase in force applied for all age groups. Thus, senior subjects always applied more vertical force on the table than subjects in other groups, whatever the pace. Interestingly, an interaction between age and pace was observed for all upper joint angles, but no clear pattern emerged from these data.

The postural analysis of the lower limbs (sacrum position and hip, knee and ankle joint angles) showed no significant differences when analysed as a function of age group or work pace; and no interaction was observed for these measurements(data not shown in Table 3).

Discussion

The aim of the present study was to assess the effect of age on motor adaptation capacities when performing a repetitive task under two imposed work paces. This task comprised a phase during which component parts stored on the floor were collected followed by an assembly phase performed on an assembly table. The collection phase addressed the question of adaptation during large-amplitude movements mainly involving the lower limbs. The assembly phase was more focused on adaptation of fine movements of the upper limbs. In this context, adaptability is considered as the capacity to modify, within a complex environment, the response dedicated to a motor task in response to changes to parameters which are internal or external to the subject.

The younger age group in our study were not as young as in many studies of interest to age. However, as explained by Ilmarinen (2001) in his review of studies involving ageing workers, an adult can be considered physiologically "young" until the age of 30. The trend for declining functional capacities can become critical after the next 15 to 20 years if the physical demands of the work performed remain the same. Therefore, we assumed that the functional capacities of our young group were close to those generally described in the literature for people aged less than 30. The results from our tests of functional capacities endorsed this conclusion (Desbrosses and Meyer, 2012). Moreover, little information is available about the 30- to 35–year-old group, even though this age is considered to precede a turning point in functional capacities.

Capacity to adapt to the task

When the task was performed at a comfortable work pace, all subjects could execute it as prescribed. In this condition, the external constraints can be considered to be the same as those found on a factory production line when no additional events disturb production. All subjects, regardless of age, were able to adapt their motor capacity to the requirements of the task. Thus, they were able to adapt the pace, amplitude and speed of movements required to collect and assemble component parts. However, the youngest group were better able to maintain a constant pace than the two older groups.

Adapting the rhythm of work to the fast work pace was difficult for all age groups. Only 7 of the 65 participants were able to maintain the pace throughout the duration of the test. Most of the remaining subjects managed to adapt to the pace demanded with only a few lapses of rhythm, which they always made up. The delays observed were often due to incidents such as dropping a nut when starting to screw it onto the threaded rods. In addition, the oldest subjects were less capable of increasing the speed at which parts were collected. Adaptation of motor capacities to the fast pace appeared to require more time with age.

A small number of subjects, mainly older individuals, were unable to adapt to the faster pace. Limitations to adaptability were generally related to motor difficulties observed during collection of the parts stored on the floor, and these difficulties were further reinforced by the increase of the work pace. It therefore appears that the age-related difficulties to adapt are closely linked to use of the lower limbs in the task.

Motor capacities adaptation and lower limbs

The way the supply bins were arranged on the floor required subjects to use their whole body when collecting component parts. Our experimental set up was deliberately non-ergonomic, but unfortunately still reflects some real-life industrial work stations. Squatting to pick up loads is generally acknowledged as the correct technique to reduce the risk of back injury (Chaffin 1987, Mc Gill et al. 1996, Fathallah et al. 1998, Chaffin et al.1999). However, this technique also involves considerable movement of the trunk and requires a whole-body upwards thrust to return to the upright position. Therefore, it represents a greater physiological effort than stooping (Kumar 1984). The quadriceps have been shown to be extensively involved in performing the squat technique (Trafimow et al. 1993).

In our study, the speeds of flexing and extending the lower limbs were found to decrease with age. Loss of efficiency of the lower limb muscles with ageing has been previously described (Macaluso and De Vito 2004). This loss of efficiency already appears significant for older subjects, who are nonetheless led to remain active for longer. Reduced production of muscular force at the knee joint was observed for the senior group in our study, as described in our previous publication (Desbrosses and Meyer 2012). This reduced force affected the kinematics of large-amplitude rapid movements. These results match those described in the review by Duchateau et al. (2006), and the loss of efficiency increases as the pace accelerates. Even so, senior subjects can still adapt to a faster pace. Thus, they can increase flexion and extension speeds to follow the rapid pace. However, their overall speed remains slower than that measured for younger subjects.

Fatigue does not appear to be an explanatory factor of this study. Indeed, no variation in speed was measured over the 20-minute tests, whatever the age group or pace. The most significant problem faced by the senior group seems to be a loss of capacity to link actions. Thus, older subjects could no longer use the time spent squatting as a means for adaptation. Younger subjects, in contrast, could minimise the time spent squatting to collect component parts by linking flexion and extension in one movement. However, with increasing age, it becomes more difficult to reduce this time. This observation can be explained by the fact that force production is more affected during rapid movements than during slow movements (Duchateau et al. 2006). Therefore, it seems that younger subjects have sufficient potential strength to “smooth” the three actions of “flexion – taking parts – extension” into a single movement as the work pace increased. Conversely, the reduction of muscular strength with increasing age accentuated the dissociation of these actions into distinct movements during collection of parts.

The major constraint imposed on the lower limbs by the squat appears to be avoided by using a stooping technique (Trafimov et al. 1993). However, stooping still demands significant effort from the back muscles (van Dieën et al. 1999, Zhang et al. 2000, Bazrgari et al. 2007). Thus, squatting was the mode most often used by our population to collect parts from the floor. Nonetheless, we observed that senior subjects systematically reduced the pelvis lowering distance. From our observations it is impossible to report a passage from squatting to stooping, unlike with the fatigue induced by the tasks observed by Trafimov et al. (1993). Indeed, the amplitude of knee flexion in older subjects in this study was within the range defining a squat (Whitney 1958, Burgess-Limerick and Abernethy 1997).

Squatting was thus used most in our study. Perhaps this observation can be correlated with the extensive campaigns aiming to prevent back pain. Nonetheless, when no recommendation was given to participants, a small percentage of subjects stooped to collect parts. Interestingly, the population using a stooping technique was mostly composed of senior subjects. We do not have information on the reasons why subjects chose to use one technique or the other. In addition, we cannot explain why they varied from one to the other during a work session. However, these habits or changes were independent of the subjects' back flexibility, height or weight.

Fluctuations between squatting and stooping were also observed by Burgess-Limerick et al. (2001) in young subjects. For these authors, the transition from one technique to the other appeared to be part of a compromise between the biomechanical advantages of the two techniques, and the influence of lifting height on this compromise. However, in our study lifting height was constant as parts were always placed on the floor; it was therefore not a determinant factor. In addition, stooping did not appear to be systematically linked to a desire to save time. Indeed, for subjects using both techniques, changing from one to the other was not always linked to increase pace. Since stooping was mainly observed with senior subjects, loss of strength and action speed of the different lower limb muscles emerges as the dominant hypothesis explaining its use.

Motor capacities adaptation and upper limbs

The second phase analysed in this study was the assembly of the component parts following their collection. This phase is more linked to fine motor skills. The upper limbs are involved in completing a task requiring manual dexterity, while the lower limbs are used to regulate postural balance. As expected, the posture of the lower limbs, strongly conditioned by the arrangement of the workstation, was not modified by age or work pace. Similarly, although statistical differences for shoulder angles were observed, their amplitude variations were low and they were difficult to interpret.

In relation to upper limb motricity, both gross (Mathiowetz et al. 1985) and fine (Desrosier et al. 1995) dexterity are known to diminish after age 60. During tests performed to assess the functional capacities of the subjects participating in this study (Desbrosses and Meyer 2012), we observed a reduction in fine dexterity comparable to that described by Desrosier et al. (1995). Nonetheless, during assembly, this reduction did not appear to be a major obstacle to completing the task. In fact, at both work paces, all age groups completed the assembly within similar time frames. In addition, the loss of fine dexterity did not appear to interfere with the adaptation process, as all subjects reduced the duration of this phase to a similar extent when the pace increased.

However, as the fine movements of the fingers could not be recorded during the experiment, it is not possible to determine whether or how age affected the method used to adapt the way parts were assembled. Adaptability of all subjects to the pace could be supported by the fact that senior subjects preserved muscular force in their upper limbs, with the same fatigability as for younger subjects (Macaluso and De Vito 2004, Duchateau et al. 2006). However, the similar speeds recorded for older subjects and the youngest subjects during the assembly phase contrasted with results reported by Cole et al. (2010). This apparent discrepancy could be explained by the fact that our seniors group was younger than theirs. Indeed, the senior participants in our study had only recently retired or were still at work, and the strength in their upper limbs was similar to that measured for the younger groups (Desbrosses and Meyer. 2012). In addition, we must keep in mind that the fine motor skills observed here concerned essentially engaging nuts on threaded rods. This task accounts only for a part of the assembly phase, with a much larger proportion of time spent screwing the nuts into the end position, which requires less fine motor skill.

Nevertheless, while seniors participants were able to adapt their assembly time to meet the required pace, they always applied more force during assembly than the youngest subjects. Increased grip force with age when handling objects between two fingers has been well documented (Cole 1991, Cole et al. 1999, Parikh and Cole. 2012). Part of the explanation given by these authors was that it increases the safety margin to avoid dropping the object when holding it still or moving it. This adaptation would compensate the lack of sensitivity due to advancing age. Motor coordination between grip force and the vertical acceleration of an object is not affected by advancing age (Gilles and Wing 2003). However, several factors may be causally related to the increase of grip force. The way in which an object is gripped and manipulated can differ with age, and may modify the level of force in the grasp (Cole et al. 2010). A lack of well-coordinated synergy between fingers has been observed for older subjects, and was linked to an increase in force (Olafsdottir et al. 2007). Another effect is increased lateral wrist speed, which is also known to increase the force applied (Werremeyer and Cole 1997).

We also need to take into account the fact that the assembly tasks in our study combined work by both hands. It is therefore difficult to attribute the increase of vertical force exerted on the table to the action of one hand or the other. The increasing force may either result from greater pressure exerted by the hand stabilising the object on the table, or from stronger force from the hand screwing the nuts to final position, or from a combination of the two. Regardless of its origin, the overall force increased with age and work pace. Thus, increasing the pace augments the force used. The two adaptation processes were combined by senior subjects who increased constraints and efforts when performing the required movements over long shifts. This increased use of force in seniors is another factor explaining why older workers are more susceptible to develop musculoskeletal disorders.

In conclusion, most subjects in the three age groups studied could adapt their motor capacity to comply with an increased work pace when performing a prescribed repetitive task. However, adaptation in older subjects was less effective than in younger subjects, with older subjects taking longer to implement the increased pace, and some failing completely. Different types of adaptation can be distinguished. Some appear to be related to the time constraints imposed by the work pace. For example, this was observed during collection of the component parts by the reduction in the amplitude of lower limb flexion; when assembling the parts, it was illustrated by the increase in vertical force applied by the hands. Other adaptations appear to be more specifically linked to the change of physical capacities with age. For instance, younger subjects were better able to increase the speed of lower limb movement, whereas older subjects further increased the vertical force applied when assembling parts. Although older subjects were capable of performing the assemblies under the different imposed conditions, increasing the work pace exacerbated their motor limitations. These limitations were particularly present when movements performed mainly involved the lower limbs. In contrast, tasks involving the upper limbs were less exclusive to older subjects being capable of performing them at the same speed as younger subjects. The motor adaptations observed provide us with a better understanding of the additional efforts required from workers when responding to an increased work pace, whatever their age. However, in our task, assembling parts can be considered as the core of the work performed, as it required certain skills. In contrast, collecting parts is an ordinary action required to complete the assembly. Thus, senior workers were still able to perform the core of the task correctly. If the workstation had been more ergonomically designed, they would have had less difficulty completing the prescribed task. This knowledge could be helpful in maintaining an older working population in conditions which help protect their health.

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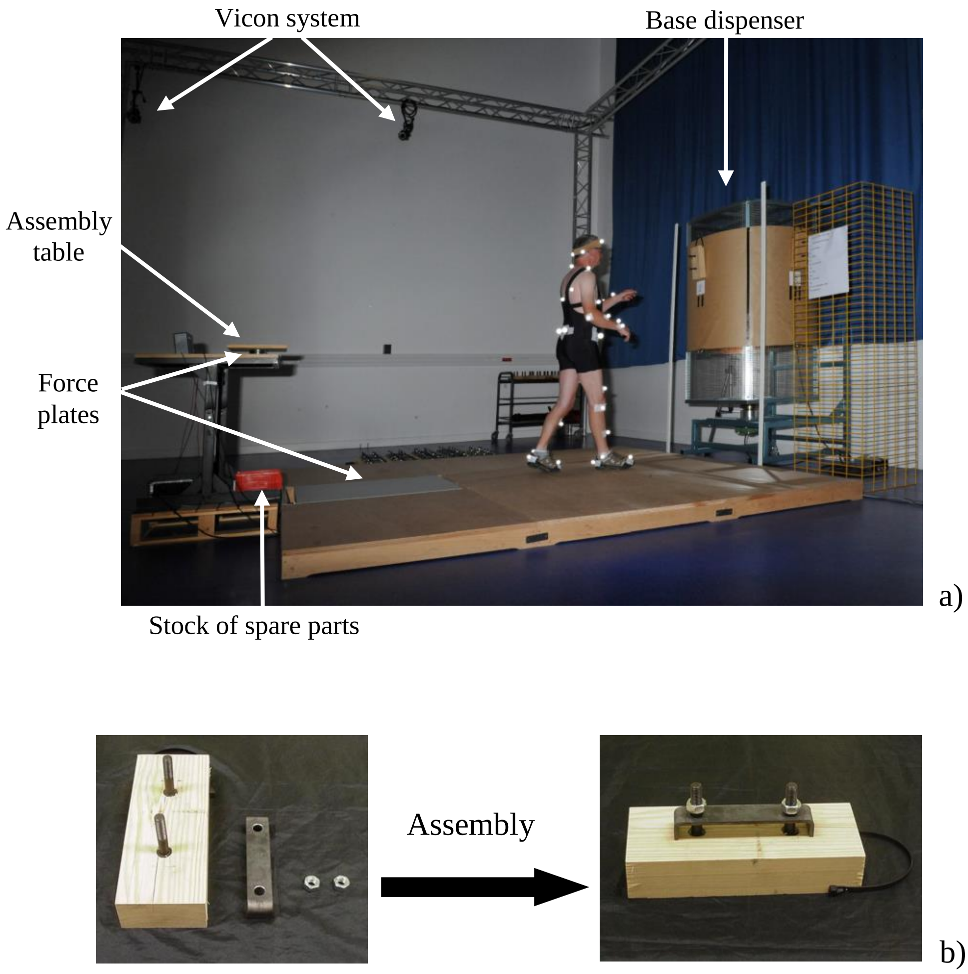


Figure 1: Experimental set-up

a) Work station: three activity phases were identified during each mounting cycle: i) a moving phase between the base dispenser and the assembly table before and after collecting and assembling the parts; ii) a collecting phase where the subject grasped a handle and two nuts in the stock of component parts; iii) an assembly phase performed on the assembly table, where the subject assembled the parts. The base dispenser was divided into four identifiable parts so that subjects could check their conformity with the pace and calculate possible delays.

b) Assembly: (left) parts before assembly: a base composed of a wooden block into which two threaded rods are inserted, a handle and two nuts; (right) the assembled parts. Assembly consisted in placing the handle on the threaded rods and fixing it with the two nuts.

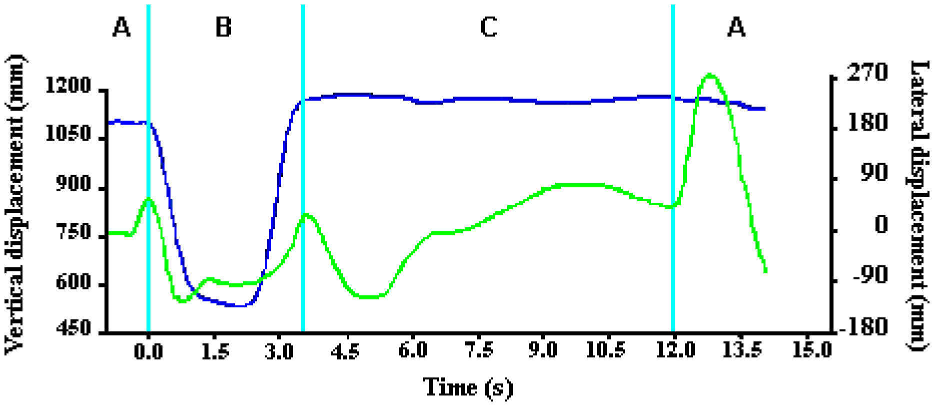
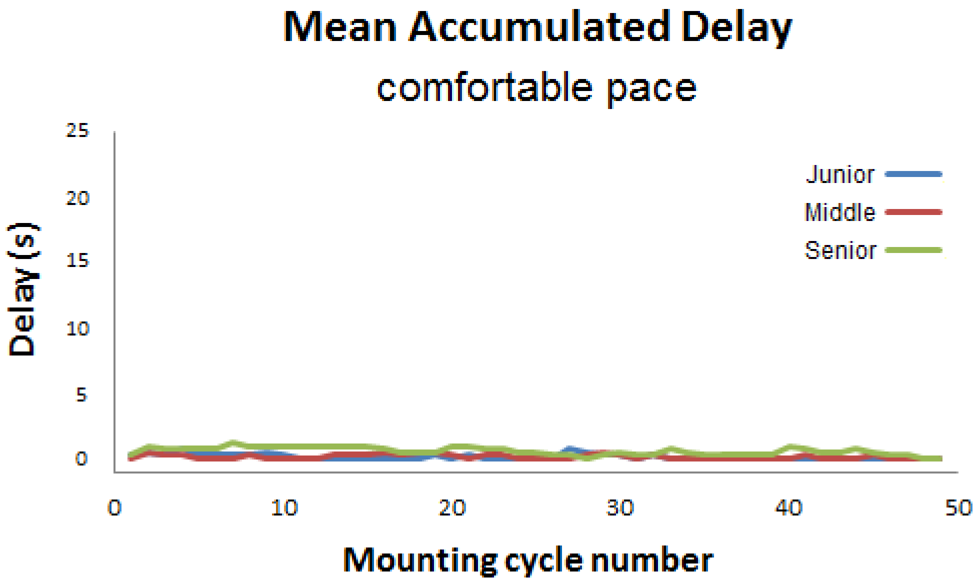


Figure 2: Example of lateral (green line) and vertical (blue line) sacrum displacement during a mounting cycle recorded for a senior subject working at the comfortable pace. Data recording started when the subject walked towards the assembly table and stopped when he stepped off the ground force plate after completing the assembly. To compare trials between subjects and for the same subject, data were synchronized with a characteristic event corresponding to the beginning of the downward vertical sacrum displacement (at the blue line separating A from B). Three activity phases of the test can be identified from the curves: A) the moving phase; B) the collection phase and C) the assembly phase.



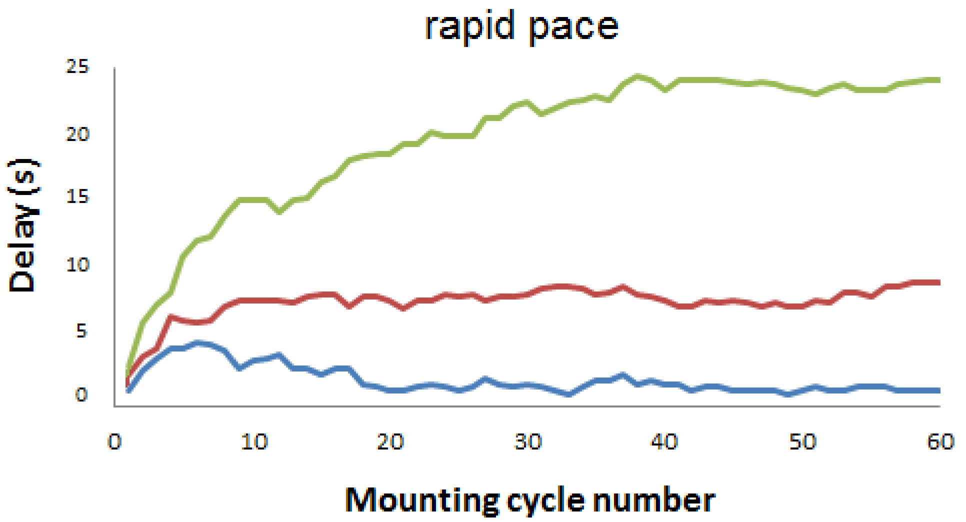


Figure 3: Mean capacity for Junior (blue), Middle-age (red) and Senior (green) groups to conform to the comfortable or rapid paces imposed for the task. The base dispenser was set up to control how well the subject groups worked in rhythm. The delay is calculated from the mean value for all the subjects from a single age-group, the time required to complete a full mounting cycle (moving phase + collection phase + assembly phase). The expected response is a plateau value equal to 0. If subjects persistently perform more slowly than the pace required, the curve rises. If they catch up, the curve drops. If the work rhythm stabilises to correspond to the imposed pace the curve reaches a plateau.

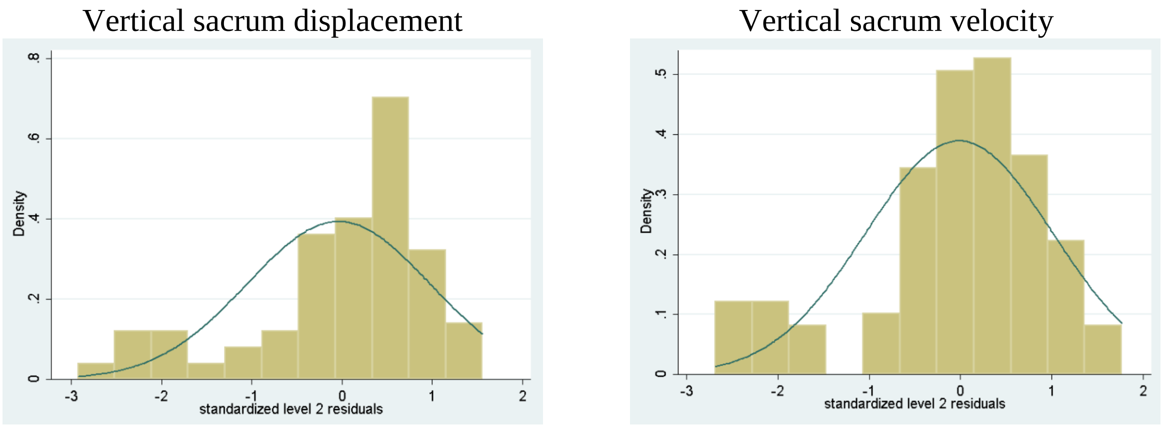


Figure 4: Distribution of vertical sacrum displacement and vertical sacrum velocity values measured for all data. The split into two groups of the data can be observed from the graphs.

Subject characteristics	Junior	Middle-aged	Senior
Number of subjects	20	22	23
Age (years)	32.6 (30-35)	47.1 (45-50)	61.8 (60-65)
Body Mass (kg)	74.9 (53-103)	78.1 (60-110)	81.2 (62-106)
Height (m)	1.77 (1.55-1.87)	1.74 (1.63-1.91)	1.74 (1.65-1.88)
Body Mass Index	23.91 (22.06-29.45)	29.39 (22.58-30.15)	29.82 (22.77-29.99)

Table 1: Mean (range) characteristics for the three subject groups.

	Comfortable pace			Rapid pace			p values		
	Junior	Middle -aged	Senior	Junior	Middle -aged	Senior	between age	between pace	inter-action
t-collection (s)	3.44 (0.76)	3.90 (1.26)	3.99 (1.05)	3.16 (0.66)	3.49 (1.08)	3.80 (1.06)	0.04	< 0.001	< 0.001
a-flexion (m)	0.52 (0.08)	0.49 (0.08)	0.46 (0.09)	0.49 (0.07)	0.47 (0.08)	0.45 (0.08)	0.02	< 0.001	< 0.001
v-flexion ($m.s^{-2}$)	0.54 (0.11)	0.47 (0.09)	0.42 (0.08)	0.54 (0.10)	0.50 (0.10)	0.46 (0.09)	< 0.001	0.90	< 0.001
t-squat (s)	1.08 (0.65)	1.38 (1.11)	1.35 (0.91)	0.93 (0.54)	1.19 (0.95)	1.33 (0.93)	0.24	< 0.001	< 0.001
v-extension ($m.s^{-2}$)	0.45 (0.11)	0.40 (0.09)	0.36 (0.09)	0.47 (0.10)	0.43 (0.09)	0.38 (0.09)	< 0.001	< 0.001	0.08
F-right knee (°)	121.11 (10.59)	116.53 (13.21)	111.87 (17.65)	120.70 (11.62)	119.84 (10.64)	110.68 (15.35)	0.007	0.004	< 0.001
F-left knee (°)	111.72 (14.36)	113.27 (14.67)	104.96 (15.62)	112.46 (10.81)	110.33 (14.66)	104.35 (13.17)	0.005	0.91	< 0.001
F-right hip (°)	134.34 (31.78)	146.46 (24.72)	143.52 (28.53)	146.20 (24.49)	133.19 (29.56)	144.72 (28.31)	0.09	< 0.001	< 0.001
F-left hip (°)	144.68 (22.58)	150.33 (22.91)	141.57 (25.99)	144.86 (21.47)	149.67 (21.30)	143.57 (25.34)	0.38	0.35	0.69
A-right hip (°)	17.59 (29.35)	3.30 (36.09)	7.61 (31.49)	15.76 (22.56)	21.06 (23.22)	17.07 (25.09)	0.02	0.07	< 0.001
A-left hip (°)	15.54 (29.81)	-5.90 (36.56)	6.10 (31.13)	23.37 (21.68)	20.85 (21.69)	13.94 (24.17)	< 0.001	< 0.001	< 0.001

Table 2: collection phase data statistical analysis: only data with sacrum vertical down amplitude higher than 0.25 m and a flexion velocity higher than 0.3 $m.s^{-1}$ were retained for this analysis. Mean values (sd) of all the tests for each group of subjects obtained for each variable considered during each pace. t = time; a = amplitude, v = velocity; F = flexion; A = Abduction.

	Comfortable pace			Rapid pace			p values		
	Junior	Middle-aged	Senior	Junior	Middle-aged	Senior	between age	between pace	inter-action
t-assembly (s)	12.7 (2.5)	12.0 (2.8)	12.8 (2.8)	11.4 (2.6)	10.7 (2.8)	11.3 (3.1)	0.08	< 0.001	0.92
Vertical force (N)	22.11 (6.11)	23.30 (8.73)	28.00 (8.91)	22.54 (7.68)	26.46 (9.48)	31.46 (10.71)	0.002	< 0.001	0.08
F-right shoulder (°)	25.00 (12.52)	25.95 (12.43)	33.44 (14.60)	27.43 (10.97)	30.06 (12.88)	35.88 (12.81)	0.02	< 0.001	< 0.001
F-left shoulder (°)	23.84 (10.95)	23.55 (10.39)	32.70 (12.45)	29.32 (11.14)	29.49 (11.12)	34.25 (12.37)	0.02	< 0.001	< 0.001
A-right shoulder (°)	2.65 (8.01)	5.88 (10.02)	5.70 (7.94)	2.42 (10.04)	4.97 (8.77)	4.04 (10.57)	0.32	0.42	< 0.001
A- left shoulder (°)	10.89 (8.77)	13.87 (9.17)	10.24 (6.46)	12.04 (9.24)	11.40 (9.23)	12.70 (7.80)	0.20	< 0.001	< 0.001

Table 3: assembly phase data statistical analysis: mean values (sd) for all tests performed with each group of subjects obtained for each variable considered during each pace. t = time; F = flexion; A = abduction.