The CAM test: a novel tool to quantify the decline in vertical upper limb pointing movements with ageing

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ORIGINAL ARTICLE

The CAM test: a novel tool to quantify the decline in vertical upper limb pointing movements with ageing

Caroline Ansay[1,2] · Mario Manto[1,2] · Stéphane Camut[1,3] · Kim van Dun[4] · Peter Mariën[4,5] · Christophe Habas[6] · Florian Bodranghien[1]

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Abstract

Background and aim Although upper limb movements in the vertical plane are very commonly used during the activities of daily life, there is still a lack of a reliable and easy standardized procedure to quantify them. In particular, ageing is associated with a decline in performances of coordinated movements, but a tool to quantify this decline is missing.

Methods We created a novel portable test called counting arm movement test (CAM test). Participants were asked to perform fast and accurate successive pointing movements towards two fixed targets (mechanical counters) located in a vertical plane in the parasagittal axis during three different time periods (15, 30, 45 s). Each upper limb was assessed separately. The test was evaluated in a group of 63 healthy subjects (mean age ± SD 49.1 ± 19.8 years; F/M 33/30; range 18–87 years).

Results Motor performances (number of clicks) significantly decreased as a function of age for both the dominant side (age effect; linear regression; $p < 0.0001$ for 15, 30 and 45 s) and the non-dominant side (linear regression; $p < 0.0001$ for 15, 30 and 45 s). Performances on the dominant and non-dominant side were linearly correlated with the time periods ($p < 0.0001$ on both sides). The symmetry index (ratio of performance on the dominant side divided by performance on the non-dominant side) was correlated linearly and positively with the duration of the test ($y = 0.002x + 1.053$; $p = 0.0056$). We also found a linear relationship between upper limb length and motor performance on the non-dominant side for 15 s ($p = 0.023$) and 45 s ($p = 0.041$). The test was characterized by a very high correlation between the results obtained by two investigators during two successive sessions in a subgroup of 7 subjects (Pearson product moment correlation: 0.989 for the dominant side and 0.988 for the non-dominant side).

Conclusion The CAM test appears as a robust and low cost tool to quantify upper limb pointing movements. In particular, the test strongly discriminates the effects of age upon motor performances in upper limbs. Future studies are now required to establish the sensitivity, specificity and reliability of this procedure in selected neuromuscular or skeletal diseases affecting the elderly.

Keywords Pointing · Movements · Timing · Counter · Gravity

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✉ Mario Manto
mmanto@ulb.ac.be

1 Unité d'Etude du Mouvement, Fonds de la Recherche Scientifique, ULB-Erasme, 808 Route de Lennik, 1070 Brussels, Belgium

2 HELB Ilya Prigogine, Campus Erasme, Route de Lennik, Brussels, Belgium

3 HELB Ilya Prigogine, Collège d'ergothérapie de Bruxelles(CEbxl), Campus Erasme, Route de Lennik, Brussels, Belgium

4 Clinical and Experimental Neurolinguistics, Vrije Universiteit Brussel, Brussels, Belgium

5 ZNA Middelheim General Hospital, Lindendreef 1, Antwerp, Belgium

6 CHNO, Hôpital des Quinze Vingts, Rue de Charenton, Paris, France

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Introduction

During activities of daily life, upper limb pointing movements against gravity are very regularly used, starting from early infancy to the elderly. For instance, grabbing a cup located in front at the height of the shoulder or above, opening a cabinet door in a kitchen, touching a button on a vertical screen are amongst the most common tasks. These tasks require a coordinated movement of the upper limb towards a visual target located in front of the subject. These movements combine a vertical saccade (a fast vertical movement of both eyes) and a movement of the upper limb. However, we miss a standardized procedure to quantify the performance associated with these kinds of movements either in a laboratory or a clinical setting.

Slowness of movements is a main feature of goal-directed movements in older adults [1]. Subjects exhibit a greater difficulty to execute multi-joint coordinated movements as compared to single-joint movements, especially when the task requires an oculomotor movement and a simultaneous movement of the limb [2–4]. Ageing decreases the ability of subjects to adapt eye movements to behavioral constraints during eye–hand coordination tasks [4]. There is currently a need for a tool evaluating the effects of ageing on fast pointing movements.

Since upper limb movements are often impaired in neurological patients, rehabilitation teams currently face a lack for a standardized procedure that would allow an easy quantification of pointing movements against gravity. Horizontal pointing movements towards fixed targets have been assessed previously using mechanical counters [5, 6]. Subjects were seated in front of the two targets (consisting of the buttons on the top of the counters). They were asked to point quickly and accurately between the two targets over a given period of time. This test is very reproducible and easy to perform. It is highly sensitive to detect coordination deficits. However, its major weaknesses are that (1) the movements are mainly performed in the horizontal plane and not purely executed against gravity, and (2) the distance between the moving shoulder and the targets is not standardized. Therefore, we thought to set up a novel test to characterize pointing movements in the vertical plane. The goal of this procedure is to provide a new tool to quantify the visuo-motor performance for the upper limbs. Such a tool would be very useful not only to estimate the motor performances of subjects at a given time, but also for the follow-up of neurological disorders in the elderly or diseases of the musculoskeletal system during rehabilitation programs or specific therapies.

Materials and methods

Participants also called subjects were recruited (procedure used to recruit: word-of-mouth; subjects mainly recruited randomly on the university medical campus) by one investigator (CA).

The following exclusion criteria were applied (on the basis of the anamnesis with each participant): history of cranial or upper limb trauma, known central nervous system disease, neck pain, alcohol intake the day before the test, intake of drugs the day before the test. All the subjects had normal or corrected-to-normal visual acuity.

Figure 1 illustrates the experimental set-up. The subject is comfortably seated. Two mechanical counters (distance between the targets: 395 mm; this distance has been used previously see [5] on the basis of experiments showing a higher performance when compared to the distance of 350/355/360/365/370/375/380/385/390/395/400/405/410/415/420 mm; this is very likely explained by biomechanical characteristics of upper limbs in adults) are fixed on a vertical support (made of medium-density fiberboard MDF) in front of the subject (width of targets: 10 mm). The apparatus lies on a table. Undesired movements are prevented with the use of a dedicated anti-skid plastic and the presence of a piece of wood on the bottom of the apparatus at the height of the table (to prevent backwards movements). Each upper limb is assessed separately, with an alignment of the corresponding shoulder in the vertical plane passing through the targets. The distance between the investigated shoulder (the anatomical landmark was the tip of the acromion process detected using palpation) and the button of the lower counter (aligned horizontally at the level of the shoulder for each subject) is 85 % of whole upper limb length defined as the distance between the tip of the acromion and the extremity of the index finger (*d* in Fig. 1). This is based on previous studies addressing the neural control of pointing movements of the upper limbs [7]. The movements were performed successively as fast and as accurately as possible during three durations (15, 30 and 45 s). We selected these durations (1) on the basis of our previous experience with the horizontal pointing test, and (2) on the observation that most healthy adults report fatigue and show a decrease of motor performances (meaning the number of clicks on the counters) during successive pointing movements which outlast 50–55 s [5]. We thus decided not to use any duration longer than 50 s to avoid the decline in performance associated with the subjective feeling of fatigue in the upper limb. For each period of time (15, 30 and 45 s), three measurements were made. We counted the number of successful clicks (a successful click is defined by a click associated with an increment of one on the mechanical counter; an unsuccessful click is defined as a pointing movement without any incrementation on the counter) by summing the clicks for each counter and considered this sum as an index of motor performance. The counters were manually reset to zero after each measurement using a resetting knob. They fixed their gaze on the lower counter at the beginning of the task. Subjects started the task with the index extended and touching the

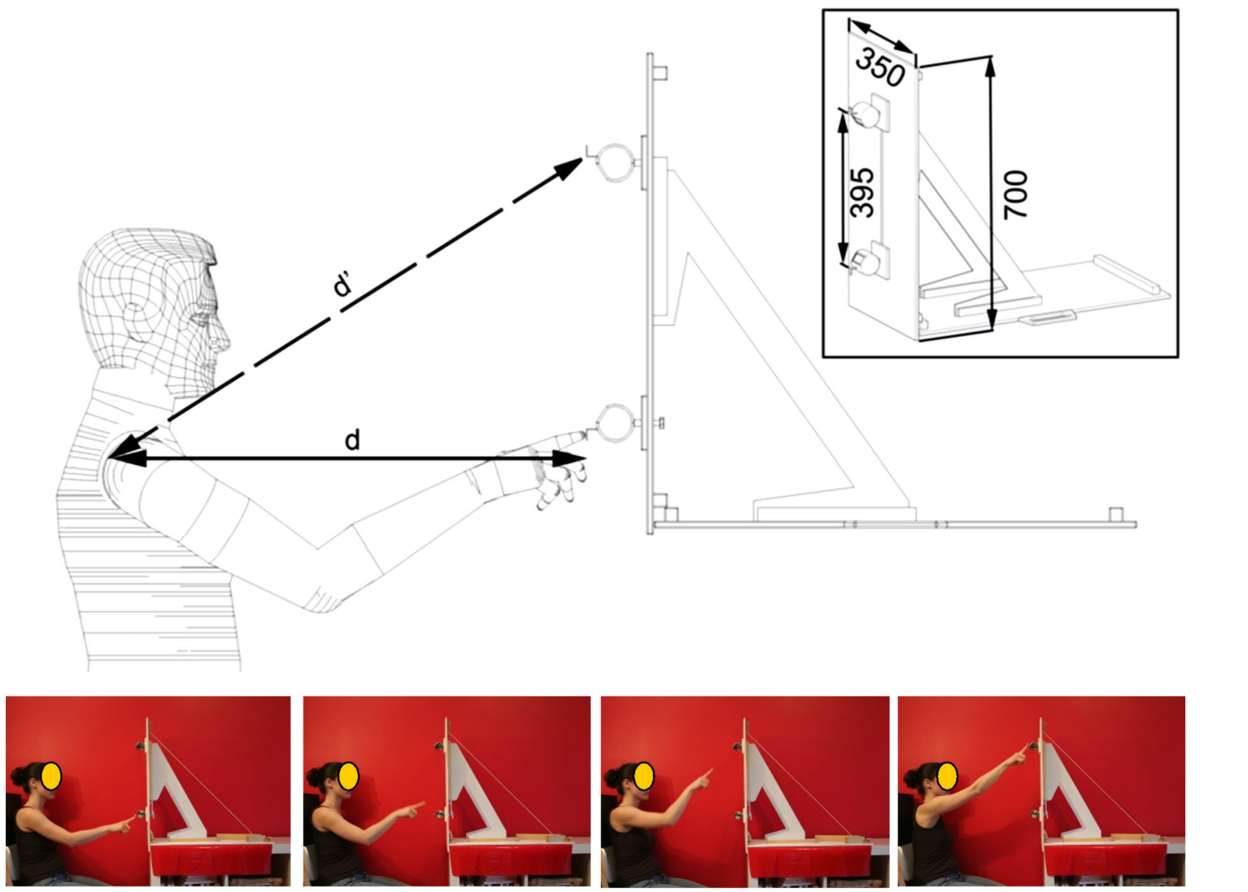

Fig. 1 Description of the task and apparatus. The mechanical counters are aligned *vertically* in the parasagittal axis of the tested shoulder. The distances *d* and *d*′ correspond to the distance between the investigated shoulder and the bottom/top counter, respectively. The device is made of wood (counters are metallic), is foldable and transportable. Dimensions are given in the *inset* (*upper right*) in mm. The *bottom part* shows an example of successive pictures taken during the pointing movements from the *bottom counter* to the *upper counter*

lower counter without pressing the button. The other fingers were maintained in flexion. Subjects were instructed orally to click (there is an audible click when the button is pressed) as quickly/accurately as possible with an emphasis of both accuracy and speed on the two mechanical counters in a successive way, after a "go" signal given orally. They were asked to stop clicking after an oral "stop" signal. The examiner used a chronometer for the "go" and "stop", and subjects were unaware of the time during the procedure. In order to take into account the learning process, each subject was allowed to perform three practice trials of 10 s for each upper limb. This number of practice trials is based on the number of trials which are applied for the horizontal pointing procedure [5]. Subjects exhibit a very fast learning of the task, and three trials are sufficient to reach the maximal performance. Between each measurement, a resting period of 15 s is used to avoid fatigue. To estimate the lateral dominance, the Edinburgh inventory was used [8]. Previous assessments with the horizontal pointing test have shown that (1) there is no influence of the first side (right or left) investigated in terms of performances on the contralateral side (left or right, respectively), and (2) a rest period between each assessment avoids carry-over effects of the previous measurement. The time to administer the test is 40 min in total. Scores of each counter were written on dedicated sheets of papers (one sheet per subject).

Table 1 lists the number of healthy subjects included in this study. We assessed 63 healthy subjects (mean age ± SD 49.1 ± 19.8 years; F 33; M 30). The majority of subjects were right-handed ($n = 59$ subjects; 4 left-handed subjects). One subject was ambidextrous (score of 20 on the Edinburgh inventory) and was excluded. One investigator (CA) conducted the assessments. In order to compare the results obtained by two investigators (CA and MM) in the same subjects, a subgroup of 7 subjects was included in a test–retest assessment. These subjects participated in two sessions the same day (one session with investigator CA and one session with investigator MM), with an interval of 15 min between the two procedures. No drop-out occurred during the study.

Table 1 Demographics of the subjects

Age (years)	Female				Male			
	n	Mean age (SD)	Handedness[a]		n	Mean age (SD)	Handedness[a]	
			Right	Left			Right	Left
18–27	6	23.8	6	0	5	23	4	1
28–37	4	29	4	0	6	32.7	5	1
38–47	3	40	3	0	7	42.6	6	1
48–57	8	53.6	7	1	2	51.5	2	0
58–67	3	64.3	3	0	6	63.2	6	0
68–77	6	74.8	6	0	2	71.5	2	0
78–87	3	82.5	3	0	2	85	2	0
Total	33	51.67 (19.97)	32	1	30	46.63 (20.04)	27	3

[a] On the basis of the Edinburgh inventory

The comparisons between the performances of the CAM test and a standardized test (grooved pegboard test) are given in the supplementary file.

Statistical procedures

Descriptive statistics were performed using Sigmastat® Software (Jandel Scientific, Germany). They were applied to the whole group of subjects. To compare the age between men and women, we applied the Student t test. The normality distribution of the data was assessed using the Kolmogorov–Smirnov test. We assessed the relation between motor performance (number of clicks) as a function of age by applying a linear regression procedure. We estimated the 95 % confidence interval and the 95 % prediction interval. To compare the performances as a function of the gender, we applied the Student t test. The same test was used to compare the length of upper limbs in male versus female, both on the dominant and non-dominant side. The same procedure was used after normalizing the scores according to the upper limb length, since our male participants had longer upper limbs as compared to females. The mean value of upper limb length in males was set at 100 % and was used to normalize the scores in females in order to obtain a normalized performance (NPi: normalized performance in a given subject):

$$\text{NPi} = \text{Performance} \times (\text{mean upper limb length in males}/\text{upper limb length}).$$

To compare the symmetry index (performance on the dominant side divided by the performance on the non-dominant side) as a function of the test duration, we applied the analysis of variance on ranks. To compare the ratios 45–15 (ratios of the performance for 45 s divided by the performance for 15 s) between the dominant side and the non-dominant side, we used the Student t test. In order to assess the influence of the distance between the index finger and each target on the number of clicks per counter (see Fig. 1: distance d' is higher than distance eye–hand), we computed the values of d' for each subject and normalized the scores of the upper counter accordingly (the score for the upper counter was multiplied by the ratio d'/d). For the correlation of the results obtained between the two investigators (CA and MM), we applied the Pearson product moment correlation.

Results

We found no difference in terms of age between the men and the women ($p = 0.32$). For the whole group of participants, the mean upper limb length was 73.5 ± 5.4 cm on the dominant side and 73.4 ± 5.2 cm on the non-dominant side. However, for both sides the mean upper limb length was statistically greater in men as compared to women ($p < 0.001$ on both sides). Figure 2 illustrates the motor performances obtained as a function of the age for the whole group of subjects and the side investigated (dominant and non-dominant). We found that motor performances decreased significantly as a function of the age for both the dominant side and the non-dominant side, and could be estimated with a linear regression procedure ($p < 0.0001$ for 15, 30 and 45 s in the two upper limbs). For both the dominant and non-dominant side, we found a highly significant linear relation for motor performance as a function of the test duration, with a positive slope of the regression line of 1.76 on the dominant side and 1.53 on the non-dominant side (Fig. 3; $p < 0.0001$ for both sides). Although some subjects started to have a feeling of slight to moderate fatigue at the level of the shoulder (at the very end of the longest duration), the performance did not decline. The values of the symmetry index (ratio dominant/non-dominant side) as a function of the duration of the test

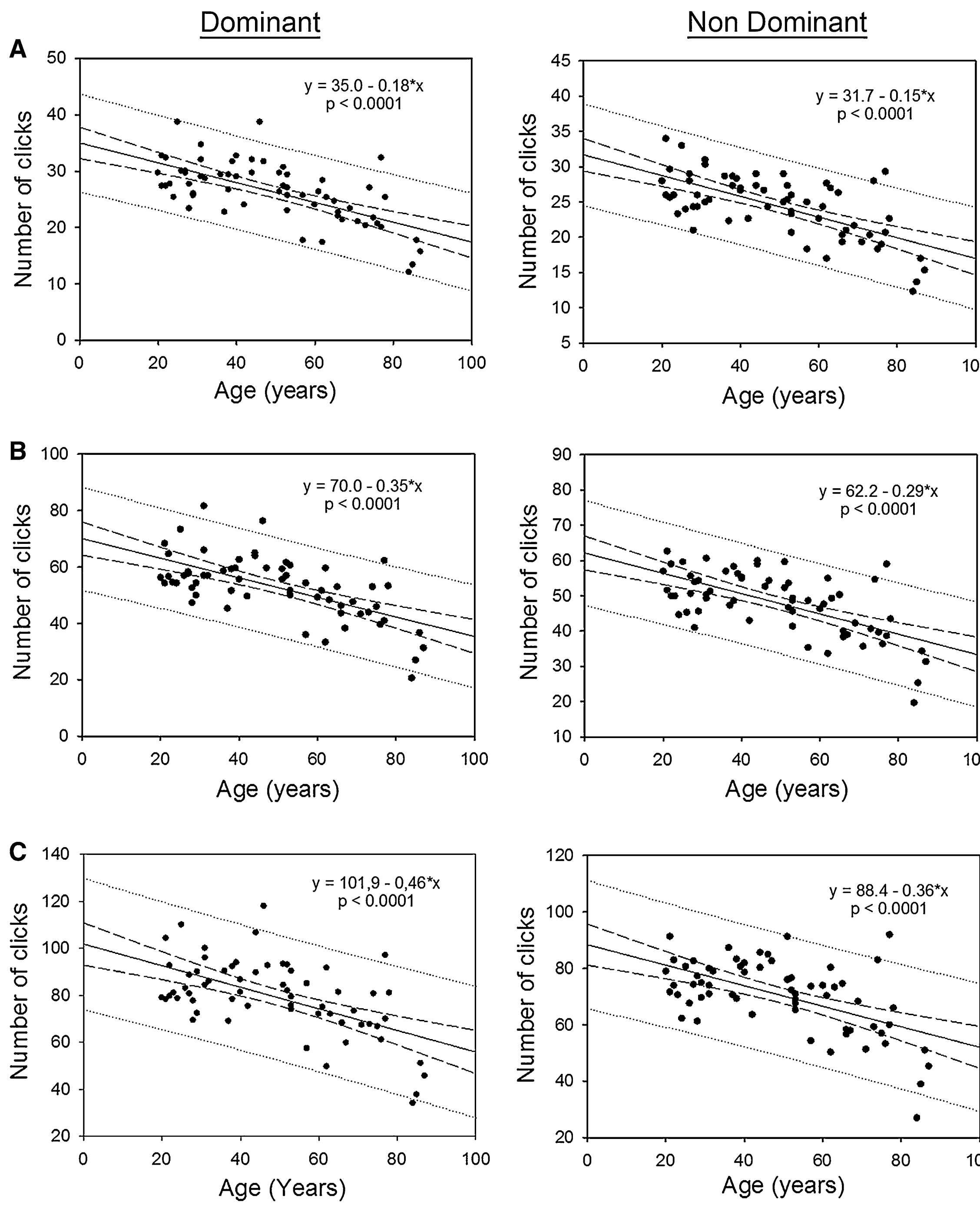

Fig. 2 Performance as a function of the age of subjects, for each upper limb in the group of 63 subjects. **a** Test duration of 15 s; **b** 30 s; **c** 45 s. The sum of clicks for the bottom and top counters are used for the *Y axis*. *Regression lines*, 95 % confidence bands (*dotted lines*) and 95 % prediction bands are shown

are illustrated in Fig. 4. A linear relationship between the test duration and the symmetry index was found ($p = 0.0056$). We observed a significant difference between the dominant side and the non-dominant side for the 45/15 ratio (Fig. 5: $p < 0.001$), showing that the motor performance was greater for the dominant side when the test duration was longer. We also looked at possible relationships between the length of the upper limb and motor performance. On the non-dominant side, we found that subjects with longer upper limb length performed significantly better (Fig. 6; 15 s: $p = 0.023$; 45 s: $p = 0.041$). In terms of differences of performances as a function of the

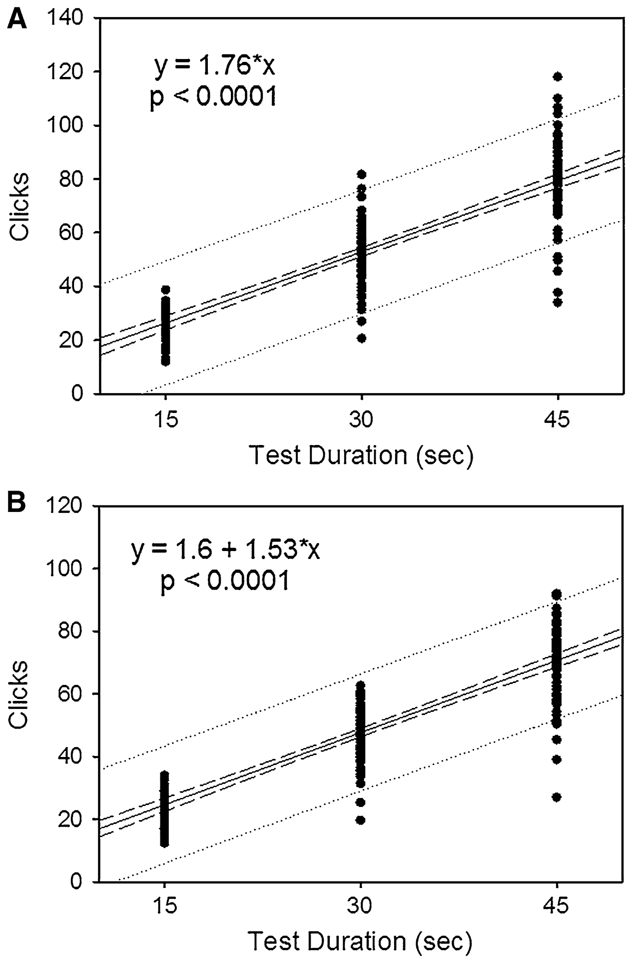

Fig. 3 Relationship between the duration of the test (15, 30 and 45 s) and motor performances (sum of clicks for the two counters). **a** Dominant side; **b** non-dominant side. *Regression lines*, 95 % confidence bands (*dotted lines*) and 95 % prediction bands are shown

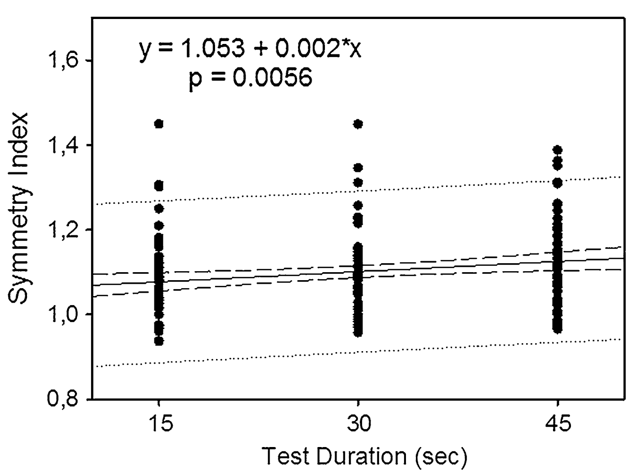

Fig. 4 Relationship between test duration and symmetry index. *Regression lines*, 95 % confidence bands (*dotted lines*) and 95 % prediction bands are shown

sex, the performances of women were statistically lower as a consequence of shorter upper limbs in our population of subjects (Table 2). Indeed, normalization of performance as a function of upper limb length cancelled the gender effects in terms of performances. We observed an effect of the distance between the shoulder and each counter. Indeed, the normalization of motor performance for each counter (normalizing for the distance between the shoulder and each mechanical counter) showed that the coefficients of linear regressions were statistically lower by normalizing the number of clicks (see Figs. 7, 8; difference between the regression slopes: $p < 0.0001$). The distance between the shoulder and each mechanical counter was thus a factor influencing the performance for each counter. We compared the results obtained by two different investigators in a subgroup of seven healthy subjects. We found highly reproducible results for both dominant and non-dominant side (Pearson product correlation coefficient: 0.989 and 0.988, respectively).

Discussion

We thus report on a novel procedure to assess upper limb pointing movements against gravity. The major findings can be summarized as follows. First, we found a highly significant linear correlation between motor performance and duration of the test. Second, we observed that age influenced significantly the performances, with a decline in the elderly. To our knowledge, this is the first procedure characterizing mathematically and with statistically significant results the decline of performances of successive fast pointing movements related to ageing. Third, our test was characterized by a better performance on the dominant side as compared to the non-dominant side, indicating that the CAM test is sensitive to handedness.

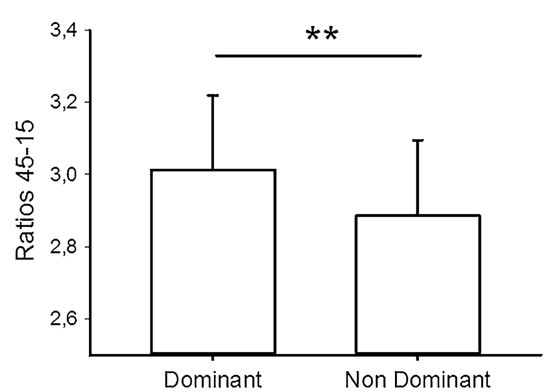

Fig. 5 Ratios of performances for longest duration (45 s) and shortest duration (15 s) as a function of the side tested. Performances correspond to the sum of clicks for the two counters. Values are mean ± SD. $^{**}p < 0.01$

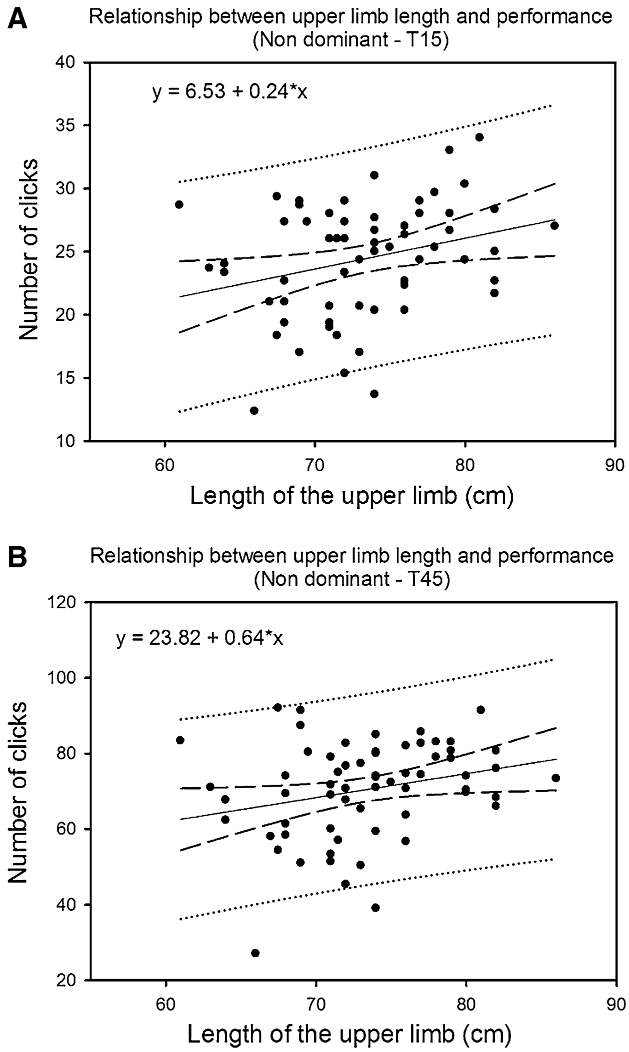

Fig. 6 Performances as a function of upper limb length. Results for the non-dominant side are illustrated (**a** 15 s; **b** 45 s). *Regression lines*, 95 % confidence bands (*dotted lines*) and 95 % prediction bands are shown

The number of clicks increased linearly as a function of the duration of the task. This is not surprising, due to the selection of the time to complete the task below the threshold (about 50 s) associated with a decline of performances. How to explain the decline of motor performances with age? The eye–hand coordination in older adults and young controls has been studied earlier [4]. Older adults exhibit difficulties in concurrent control of inhibiting hand movement and initiating eye movement within a sequence [4]. The phenomenon of gaze anchoring (gaze remains fixated on a target until the hand movement is terminated, see [9]) is impaired in the elderly. Indeed, older adults anchor their gaze to given pointing targets for a longer time when compared to young subjects [4]. As compared to the young adults, the older adults produced undershooting saccades (hypometria) and delayed gaze fixation. Biomechanical changes in the eye muscles and adjacent structures impact on vertical saccades, with upwards saccades becoming slower and hypometric with senescence [10]. In addition, the age-related degeneration of proprioception, position sense and tactile sense contribute to the decline of performances [11–18]. Overall, the coordination of multiple effectors of the motor system, such as the eye and the upper limb, is impaired with ageing, rendering the sequencing more difficult. This may explain our findings of reduced motor performances in older participants. Regarding the differences found according to the side tested (dominance), studies on motor units of voluntary muscles have identified lower average firing rates, lower recruitment thresholds, and greater firing rate/force delay in the dominant hand as compared to the non-dominant hand [19]. In addition, muscle synergies and predictive mechanisms of movement provide an advantage to the dominant side [20, 21]. These findings can contribute to the better performance on the dominant side in our subjects.

Table 2 Performance as a function of the sex

Test duration (s)	Dominant side			Non-dominant side		
	Mean performance (SD)		p value	Mean performance (SD)		p value
	Male	Female		Male	Female	
(a) Sum of clicks for the two counters						
15	28.10 (5.21)	24.75 (5.09)	0.012*	26.00 (4.16)	23.03 (4.35)	0.008*
30	56.60 (10.90)	49.63 (10.19)	0.011*	50.79 (7.64)	45.40 (9.58)	0.017*
45	84.00 (15.83)	74.88 (15.18)	0.023*	74.80 (10.49)	66.54 (13.74)	0.010*
(b) Data normalized as a function of the upper limb length						
15	28.10 (5.21)	27.48 (5.65)	0.611	26.00 (4.16)	25.55 (4.82)	0.624
30	56.60 (10.90)	55.11 (11.31)	0.558	50.79 (7.64)	50.38 (10.62)	0.851
45	84.00 (15.83)	83.15 (16.85)	0.772	74.80 (10.49)	73.84 (15.24)	0.717

* $p < 0.05$

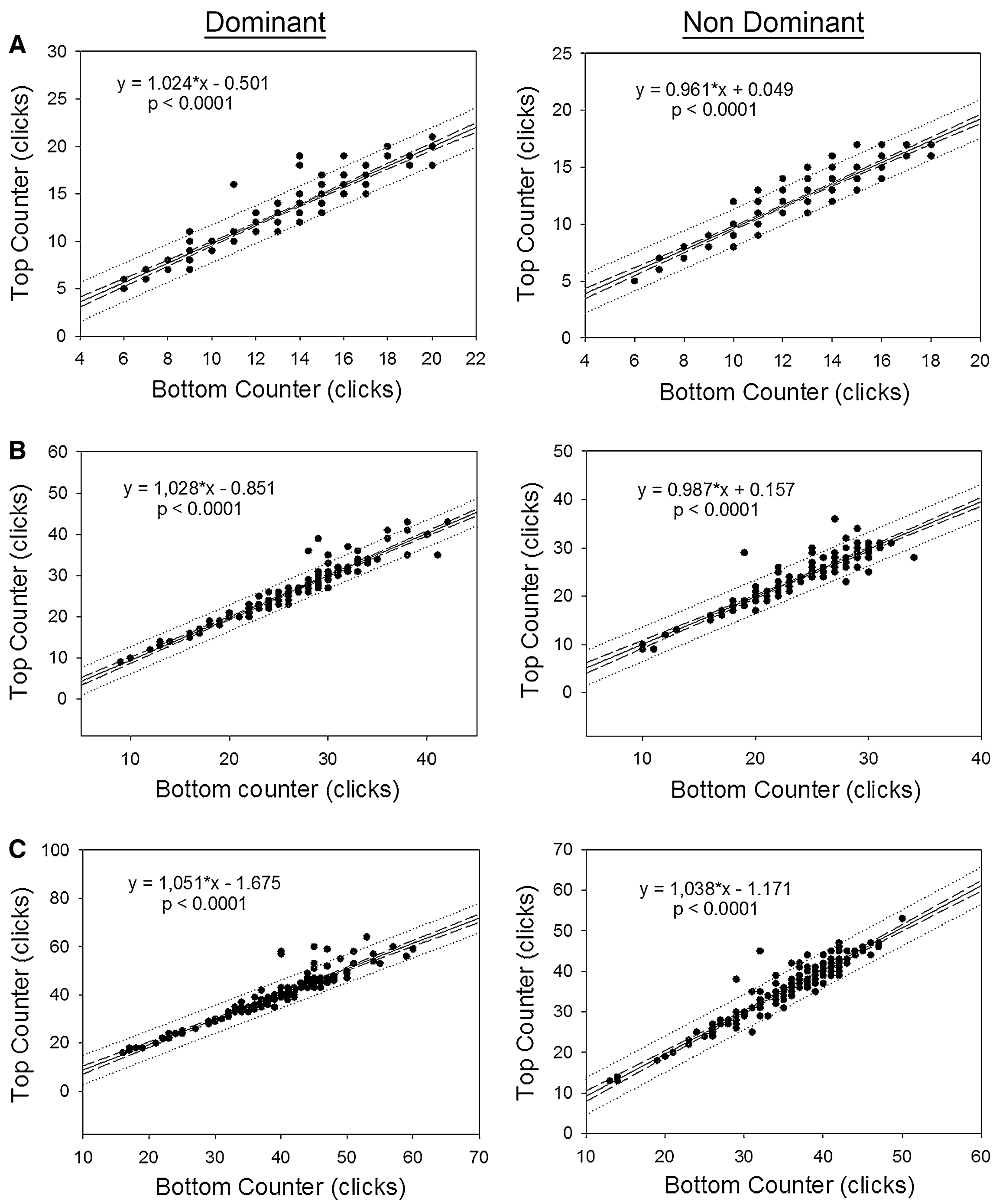

Fig. 7 Relationships between scores (number of clicks) of bottom counter and top counter. *Regression lines*, 95 % confidence bands and 95 % prediction bands are shown

The CAM test is an easy and low cost procedure to quantify the visuo-motor performances during successive vertical pointing movements for the upper limbs. This test could complement the standardized tests currently used to evaluate upper limb performances in patients, such as the box and block test or the nine-hole peg test [22, 23]. Specific studies comparing the scores of the CAM test with these two widely used are required to see whether there is a correlation or not. The CAM test was assessed here in adults, but it could be assessed in children and the distance between the two mechanical counters could be adapted accordingly in future studies.

The CAM test should now be assessed in selected neurological populations. For instance, the CAM test could

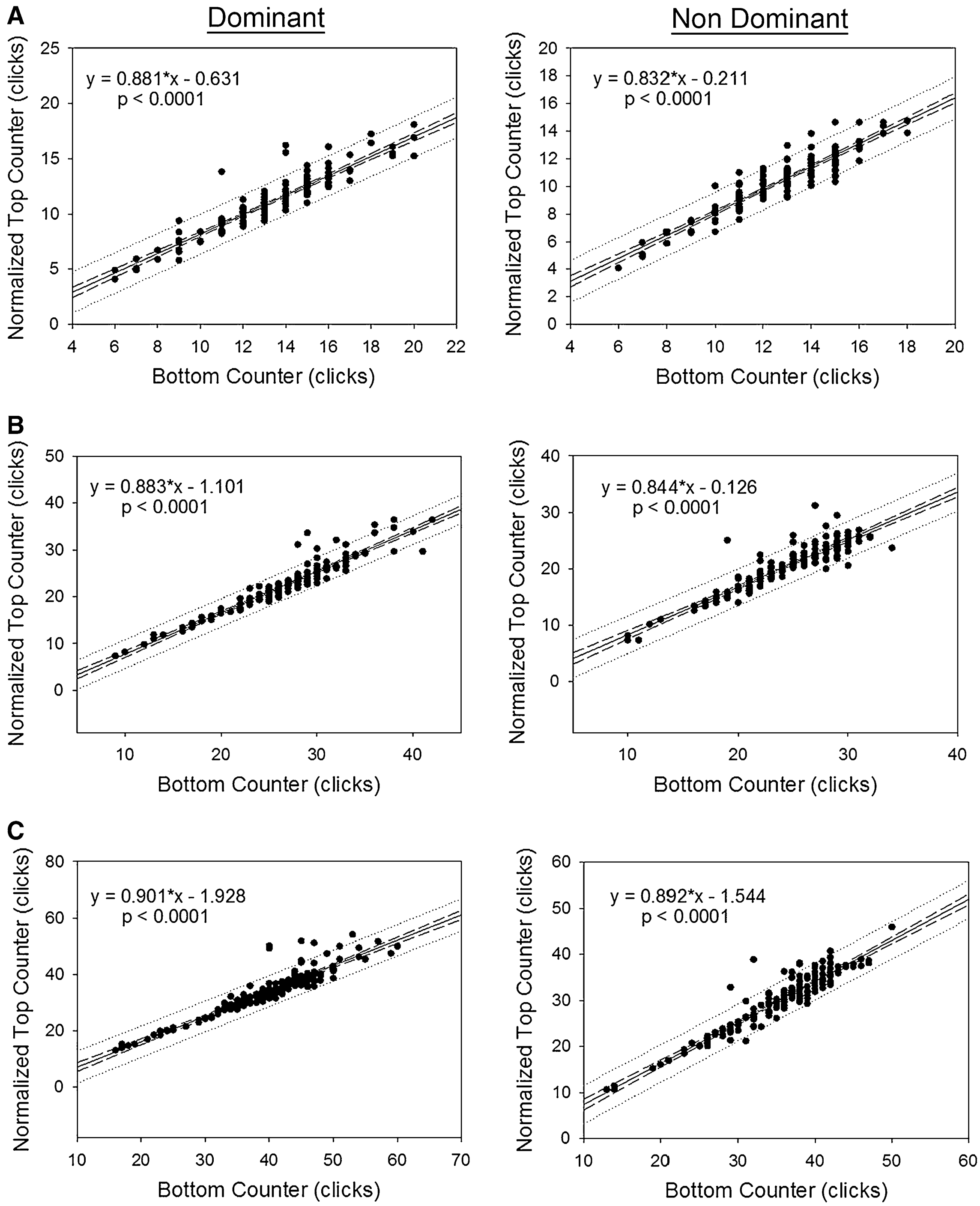

Fig. 8 Relationships between scores of lower counter and upper counter. Values of the top counter are normalized taking into account the distance between the index and the two targets. *Regression lines*, 95 % confidence bands and 95 % prediction bands are shown

be applied in patients presenting a stroke in the mesencephalon or in patients with supra-nuclear palsy, disorders affecting mainly older adults [24–26]. In these categories of patients, the generation of vertical saccades and the coordination between oculomotor movements and upper limbs are strongly impaired, but we still lack sensitive tools to evaluate these kinds of disorders in the clinic. The CAM test could also be tested in neuromuscular disorders such as myasthenia gravis, which affects shoulder muscles and presumably would be characterized by abnormal 45/15 ratios with a strong fatigue for the longest task [27]. The CAM test could also be used to evaluate patients with brachial plexus injury, especially the upper trunk plexopathy affecting C5–C6 roots. In terms of motor deficits, these patients show a proximal weakness affecting the deltoid and biceps muscle with relative preservation of hand function [28]. The CAM test is portable and the feasibility of employing this tool in clinical settings is high.

One weakness of the CAM test is that it does not provide the details of the motor performances between the successive clicks throughout the task (dynamic profile of performances) but provides a global estimation of the number of clicks over a given period of time, including for longer tasks. A computerized version providing the timing between two successive clicks would thus be very valuable. This version would also allow computing a parameter of the inter-clicks variability for successive pointing movements.

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Compliance with ethical standards

Conflict of interests The authors have no conflict of interest (financial or non-financial) to declare.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent Before starting the measurements, each subject was provided with an oral explanation of the full procedure and signed an informed consent, following approval of the study by the ethical committee ULB-Erasme.

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