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Motor Asymmetry in Elite Fencers

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Abstract

We previously reported that asymmetrical patterns of hand preference are updated and modified by current sensorimotor conditions. We now examine whether participation in long-term training in the upper extremity sport fencing might modify arm selection and performance asymmetries. Eight fencers and eight non-fencers performed reaching movements under three experimental conditions: (1) non-choice right; (2) non-choice left; and (3) choice, either right or left arm as selected by subject. The non-choice conditions allowed assessment of potential interlimb differences in movement performance, while the choice condition allowed assessment of the frequency and pattern of arm selection across subject groups. Our findings showed that the athlete groups showed substantially greater symmetry in both our performance and selection measures. These findings suggest that arm selection and performance asymmetries can be altered by intense long-term practice.

Keywords

motor asymmetry; motor lateralization; arm movement; fencers; handedness; hand preference; arm reaching; athletes

Healthy right-handed individuals tend to show a right arm preference for components of tasks that involve tool use, such as writing with a pen, cutting with a knife, or manipulating scissors. This preference is often used as an indicator of handedness, assessed with standardized questionnaires (Annett, 1970; Oldfield, 1971). However, hand preference has also been assessed during simple reaching tasks, which do not involve learned tool use. In this case, the hand chosen to reach for a target object depends on the location of the object in the workspace, such that objects on the far left of workspace are most often reached with the

left arm, whereas objects on the far right are reached with the right arm, regardless of handedness (Kim, Buchanan, & Gabbard, 2011; Leconte & Fagard, 2006; Mamolo, Roy, Bryden, & Rohr, 2004). In addition, the right arm tends to cross midline to reach into contralateral space much more than does the left arm. The results of studies on reaching preferences have led to the view that reaching preferences depend on location in the workspace, with a bias for the right arm when reaching near the midline. Handedness has also been associated with asymmetries in the performance of unimanual tasks (Bagesteiro & Sainburg, 2002; Carson, Chua, Elliott, & Goodman, 1990; Carson, Chua, Goodman, Byblow, & Elliott, 1995; Carson, Goodman, & Elliott 1992; Elliott, Chua, & Pollock 1994; Elliott, Lyons, Chua, Goodman, & Carson 1995; Flowers, 1975; McManus, Murray, Doyle, & Baron-Cohen, 1992; Przybyla, Good, & Sainburg 2012; Roy & Elliott, 1986; Sainburg, 2002; Sainburg, 2005; Sainburg & Kalakanis, 2000; Sainburg & Schaefer, 2004; Shabbott & Sainburg, 2008; Todor & Kyprie, 1980; Wang & Sainburg, 2007; Yadav & Sainburg, 2011). We have provided evidence that such asymmetries might result from hemispheric lateralization of basic motor control processes. According to this idea, the left hemisphere is specialized for predictive control of limb and task dynamics, while the right hemisphere is specialized for stabilizing limb velocity and position, through impedance control mechanisms (Yadav and Sainburg, 2014a). Further, both hemispheres appear to contribute to control of each arm (Yadav and Sainburg, 2014b, Mani et al, 2013). This has been supported by studies in stroke patients with either right or left hemisphere damage, who show hemisphere-specific movement deficits in both the ipsilesional and the contralesional arms (Schaefer et al, 2007; Mani et al, 2013). It should be stressed that during everyday activities, these specializations are usually expressed as a distribution of labor between the hands during bilateral performance. The dominant arm often performs the component of the task that requires smooth and efficient trajectory control, such as slicing with a knife. In contrast, the non-dominant arm often performs the stabilization component that must impede the forces that are imposed on by the dominant arm on the sliced object (ie. Bread). Thus, the proficiency of each arm for different aspects of tasks calls into question the idea of quantifying handedness by hand preference surveys, alone. Instead, performance asymmetries between the arms might provide a better measure of handedness than traditional preference questionnaires (Annett, 1970; Bishop, Ross, Daniels, & Bright, 1996; Bryden & Roy, 2005; Steenhuis & Bryden, 1989). We recently tested whether these two manifestations of handedness might be causally related. We measured arm preferences for reaching to an exhaustive set of targets under different sensorimotor conditions. Previous research had indicated that both the mechanical efficiency, and the spatial accuracy of movements of the right and left arms are differentially influenced by visual feedback conditions (Bagesteiro & Sainburg, 2002; Carson et al., 1990; Goble & Brown, 2008; Guiard, Diaz, & Beaubaton, 1983; Imanaka, Abernethy, Yamauchi, Funase, & Nishihira, 1995; Lenhard & Hoffmann, 2007; Sainburg, 2002; Sainburg & Wang, 2002; Wang & Sainburg, 2007). Specifically, a reversal in the right arm advantage for accuracy occurs, when reaching to a large array of targets without visual feedback. In addition, the right arm advantage for mechanical efficiency is largely reduced without visual feedback. In accord with these changes, we reported a substantial reduction in right arm reaches across midline, and a substantial increase in left arm choices, when subjects reached without visual feedback (Przybyla, Coelho, Akpinar, Kirazci, & Sainburg, 2013). These results suggested that arm

preferences reflect online decisions that are based on performance differences between the arms, which change with different task conditions. This experience-dependent plasticity in limb selection, supported by an array of previous studies (Coelho, Przybyla, Yadav, & Sainburg, 2013; Przybyla et al., 2013; Stoloff, Taylor, Xu, Ridderikhoff, & Ivry, 2011), suggests that long-term training in particular motor tasks might lead to systematic changes in performance asymmetries and/or arm selection preferences. For example, Teixeira and colleagues (2007) provided evidence that unimanual practice of sequence finger tapping with the left hand induced a persistent shift of hand preference for subsequent performance of that task (Teixeira & Okazaki, 2007; Teixeira & Teixeira, 2007). Similar observations were reported in monkeys who started using the left hand more frequently following training to reach food with that hand (Deuel & Dunlop, 1980). Interestingly, Mikheev and colleagues (2002) reported increased use of the left arm in elite judoists, compared with non-athletes. Those findings were probably related to the bilateral performance demands in judo, as fighters use both hands for attack and defense. However, because hand preference was assessed through questionnaires, no information about the effects of such training on movement performance was reported. Overall, these results suggest that training might modulate hand preference, at least in the case of the non-dominant hand. However, very little is known about the changes in arm performance and selection in groups who have extensive training with only the dominant arm.

In order to test the effects of long-term training on interlimb differences and hand preference, we recruited a group of right-handed fencers. Fencing is a combat sport in which two athletes fight indirectly, through their weapons (the foil, the sabre, or the épée), and mainly includes fast movements directed toward the opponent. We have chosen fencing because it challenges upper limb coordination extensively and focuses predominantly on training of the dominant arm. In order to assure our fencers experienced long-term and intense training, we recruited from the Penn State University fencing program, which has been recognized as one of the best in the country, with a history of developing US Olympic and US National level fencers, and winning the national collegiate championships (NCAA) prior, during and after this study was conducted. We now predict that such long-term and intensive fencing practice, which focuses predominantly on the right arm motor performance, required to reach and maintain this elite level should result in more efficient trajectories with greater accuracy in simple right arm reaching tasks, as compared to age matched non-fencers. Furthermore, it is plausible that such unbalanced training between the two arms leads to increased interlimb differences in motor performance and that this should be associated with more extensive right arm selection during a choice reaching task. Thus, our main hypothesis predicts that long-term training in our fencers should improve performance measures, preferentially for the right arm, and that arm selection in fencers should show a stronger bias for the right arm.

Methods

Subjects

Eight healthy young fencers (4 females) aged between 18-24 years old ($M=21.1$, $SD=1.6$) and eight healthy young non-fencers (4 females) aged between 18-23 years old ($M=21.8$,

SD=2.3) signed voluntarily the consent form approved by the Institutional Review Board of the Pennsylvania State University to participate in this study, which was conducted in accordance with the Declaration of Helsinki as amended by the 59th World Medical Association General Assembly, Seoul, Republic of Korea (2008). Our group of fencers' experience ranged between 6-14 (M=8.8, SD=3.2) years and they were members of the highly ranked Penn State University fencing program, as described above in introduction. Our group of non-fencers self reported no training experience in any sports. All subjects across both groups reported right-handedness and scored above 45% on the extended 35 items handedness questionnaire (Hull, 1936), which is similar to widely known Edinburgh Inventory (Oldfield, 1971).

Experimental Setup

The experimental setup was previously shown and described in detail (Przybyla et al. 2013). In short, subjects were seated at the table with sensors of the electromagnetic movement tracker (Flock of Birds, Ascension Technology, USA) attached to their right and left forearm and upper arms. Their lower arms were supported on an air sled to minimize the effects of friction and gravity, and also prevent fatigue. This setup assured reaching in the 2D horizontal space in front of the subject. Subjects' arms were covered by a mirror onto which two cursors, start positions and targets were projected from 55" flat screen TV (Sony Electronic Inc., USA), which displayed our custom virtual reality interface, Kinereach®, designed by one of the authors (RLS) and controlled by an iMac computer (Apple Inc., USA). These cursors were associated with the index finger of each arm and their position on the screen was updated in real time, limited to TV screen update of 60 Hz. Data of arm displacements (shoulder, elbow and index finger) were recorded at 130 Hz frequency during subjects' movements.

Experimental Design

Each subject underwent three experimental sessions separated from each other by at least two weeks. Each session tested one of the following conditions: non-choice right arm reaches; non-choice left arm; and choice - reaches using either right or left arm as selected by the subject on each trial. The non-choice conditions were designed to determine interlimb differences in sensorimotor performance across all targets in both groups (fencers and non-fencers). The choice condition was designed to reveal the pattern of arm selection across the groups.

All subjects performed the choice session on their first visit and then followed up with two more visits to perform the non-choice conditions, which were counterbalanced. Each session consisted of 320 reaches to thirty-two randomized targets (10 per target) across the horizontal workspace in front of the subject. To account for variation in subjects' size and arm length, the array of targets was set for each individual based on starting arm joints' configuration and maximum distance of arm reach. The start positions, each displayed as 2 cm diameter circle, were set at the location of the tip of the index finger for joint positioned at 25 deg of shoulder flexion in 90 deg abduction and 75 deg of elbow extension. In Figure 1, we show the array of thirty-two targets, each displayed as 3.5 cm diameter circle, consisted of four rows spaced by 15% of the maximum distance of arm reach with the row

closest to the body midline at 25% (row A) and the row furthest away at 70% (row D) of the maximum reaching distance. Rows A and D consisted of 7 targets and two rows in between (row B and C) consisted of 9 targets. The center targets in each row were aligned with the midline of the subjects' body and the remaining targets were spaced away from the center, half of them to the right and the other half to the left, consecutively by one quarter of the distance between the starts positions, as shown in Figure 1. In order to initiate each trial, the subject positioned both cursors (1.6 cm diameter circle with cross hairs), each representing the tip of the right or left index finger in a 3 cm diameter start circle. Once both cursors were positioned in each start circle (left and right) for 300 ms, an audiovisual "go" signal was triggered. The target for each trial was displayed prior to trial initiation, after completion of previous trial, to allow subjects to self-pace trial preparation with unlimited time for planning the movement and/or selecting the arm in the case of choice condition.

Data Analysis

The procedures and details of data analysis were similar to those previously described in Przybyla et al. (2013). In short, displacement data were collected at 130 Hz and processed using an 8 Hz dual-pass Butterworth filter. Cursor displacement data were differentiated to quantify movement speed and movement time from velocity profiles. Movement speed was defined as the peak amplitude of the velocity profile. Movement time was taken as the time between movement initiation and movement termination, which were defined as the closest local minima to the peak amplitude found below 8% of that peak amplitude on the velocity profile. These dependent variables were quantified to examine whether there were any significant differences in movement speed or movement time, which might affect movement accuracy, movement quality, or pattern of arm selection. In order to determine interlimb differences in the quality of movement performance, we quantified two dependent measures: 1) movement accuracy (Final Position Error = FPE) and 2) movement quality (Hand Path Deviation from Linearity = HPDL). The FPE was defined as the Euclidian distance between the center of the target and the 2D final position of the tip of the index finger. The HPDL was defined as the ratio between the minor and the major axis of the movement path of the index finger (hand path). The major axis was defined as the longest distance between any of two points on the hand path and the minor axis was defined as the shortest distance perpendicular to major axis. In order to examine arm selection patterns in the choice condition, we quantified the total of the right and left arm reaching frequency.

All dependent variables were subjected to a 3-way mixed model ANOVA, with group (fencers or non-fencers) as a between-subject factor, and arm (right or left) and regions of space (right, middle and left) as within-subject factors. Note that right, middle and left regions included targets to the right of midline of the body (see Figure 1, columns: 6-9), the midline of the body (column 5), and to the left of the midline of the body (columns: 1-4) respectively. For all analyses, subjects were treated as a random factor and statistical significance was tested using an alpha value smaller or equal to 0.05. For post-hoc analysis, our tests depended on whether the assumption of sphericity was violated, as tested by the Mauchly's test. If not, Tukey HSD (Honestly Significant Difference) was used for post hoc analysis. If the assumption of sphericity was violated, then post hoc for within subject factor (target) was corrected using the Greenhouse–Geisser for $\epsilon > 0.75$, or Huynh–Feldt for

epsilon < 0.75. We used the mean and the standard error of the mean to display the results in text and figures.

Results

Movement speed and duration were matched between arms and groups

Our paradigm provided movement speed criteria in order to match peak velocities and movement duration between arms and groups. Our 3-way mixed model ANOVA, arm (right or left) \times region of space (right, middle and left) \times group (fencers or non-fencers), revealed no 3-way interaction, $F(2, 70) = 1.10, p = .33, \eta^2 = .012$, nor group \times arm interaction, $F(1, 70) = 1.59, p = .21, \eta^2 = .01$, nor group \times region of space interaction, $F(1, 70) = 0.15, p = .21, \eta^2 = .002$. This confirmed that our main control for movement speed was effective. However, there was a significant region of space \times arm interaction, $F(1, 70) = 16.66, p = .0001, \eta^2 = .25$. Post-hoc analysis showed that the right arm reaches to the left space were significantly faster than the left arm reaches to other region spaces, which is somewhat expected as the right moves to the contralateral space. However, this interaction does not affect our main hypothesis, which predicts a 3-way interaction and an interaction between arm and group for our performance measures. Besides the movement speed, we also tested the movement time (MT) and tried to find whether this parameter is similar between groups and arms across regions of space. Similar to the movement speed, the statistical result for MT did not reveal a 3-way interaction $F(2, 158) = 2.69, p = .08, \eta^2 = .04$, no 2-way interaction between group and arm, $F(1, 158) = 2.69, p = .10, \eta^2 = .02$, and no 2-way interaction between group and region, $F(1, 158) = 0.08, p = .91, \eta^2 = .001$. However, an interaction between region and arm was significant, $F(1, 158) = 20.34, p = .0001, \eta^2 = .32$. Post-hoc analysis showed that the right arm had significantly slower MT in the right space compared to middle and left spaces. The similar pattern was also observed for the left arm, the left arm had significantly slower MT in the left space compared to right space. Thus, we could assume that both movement speed and MT had no effect on the accuracy, movement quality or arm selection patterns.

Effect of group on right and the left arm performance

Both groups, fencers and non-fencers, made reaches in the non-choice condition with the right and the left arm to targets located across horizontal space in front of the body. Figure 2 shows the average magnitude of the final position error (FPE) for each target for the right (black half circles) and the left arm (gray half circles) across non-fencers in Figure 2A, and fencers in Figure 2B. Figure 2C shows the average FPE for the right and the left arm in each region of space for both non-fencers and fencers. We found a significant region \times arm interaction, $F(2, 70) = 3.65, p = .03, \eta^2 = .20$ and post-hoc analysis revealed significant right arm advantage for movements into the right region of space ($p = .02$, Tukey HSD), as shown in Figure 3A. Overall, the right arm was significantly more accurate across both groups and all regions, $F(1, 70) = 4.25, p = .04, \eta^2 = .12$, as shown in Figure 3B. More importantly, the non-fencers were more accurate with the right arm in movements to the vast majority of targets, and only target A2 showed a substantial advantage for the left arm, as shown in Figure 2A. In contrast, for fencers, each arm showed greater accuracy to the majority of targets in its ipsilateral workspace, as shown in Figure 2B. In fact, the left arm of non-

fencers showed substantially larger errors than their right arm or either arm of fencers ($p < .02$, Tukey HSD), see Figure 2C. The averaged data are shown in Figure 3C. Thus, performance was more symmetric for fencers, and more asymmetrically associated with right arm performance for non-fencers as confirmed by significant interaction between arm and group, $F(1, 70) = 3.94$, $p = .05$, $\eta^2 = .11$.

Figure 4 shows the hand path deviation from linearity (HPDL), our measure of hand path efficiency, averaged for each target across non-fencers, Figure 4A, and fencers, Figure 4B. Figure 4C shows the average HPDL for the right and the left arm in each region of space for both non-fencers and fencers. Similarly to FPE results, our ANOVA showed a significant interaction between group and arm, $F(2, 70) = 5.63$, $p = .02$, $\eta^2 = .09$, which is shown in Figure 5. Visual inspection of figures 4A and 4B reveals that non-fencers made substantially straighter movements with the right arm than the left arm for most targets. However, the fencers showed straighter movements than the non-fencers for both the right and the left arms, and the HPDL was more similar between both arms of fencers than between both arms of non-fencers. Post-hoc analysis revealed that hand paths of non-fencers reaching with the left arm had significantly larger HDPL when compared to their right arm or any arm of fencers ($p < .01$, Tukey HSD).

Taken together, these results indicate a reduction of interlimb differences in FPE and HPDL for fencers, and support the hypothesis that long-term practice alters performance characteristics for reaching movements in elite fencers. However, in contrast to our initial prediction, the quality of this interaction was such that both arms of fencers were more accurate ($p < .003$) and more linear ($p < .0001$) than the corresponding arm of non-fencers.

Effect of group on arm selection symmetry

Both groups (non-fencers and fencers) were asked to choose and move one arm to one of thirty-two targets presented on each trial. That is, they could reach to the target with whichever arm they chose, and movements were self paced. Figure 6 shows distributions of reaching frequencies in the form of a pie chart for each target, averaged across non-fencers in Figure 6A, and fencers in Figure 6B. Each pie chart represents the mean percentage of total reaches made by either the left (light gray) or the right arm (black). In Figure 6C, we show that both the non-fencers and the fencers reached almost exclusively with the right arm to the targets in the right, 98.5% vs. 1.5%, $p < .05$ for non-fencers and 97.5% vs. 2.5%, $p < .05$ for fencers, and middle regions of the workspace, 93.5% vs. 6.5%, $p < .05$ for non-fencers and 76.5% vs. 23.5%, $p < .05$ for fencers which resulted in significant 3-way interaction, $F(2, 70) = 9.41$, $p = .0002$, $\eta^2 = .02$. Furthermore, both groups showed significantly more reaches with the left arm to the left region of the workspace, 91.5% vs. 8.5%, $p < .05$ for fencers, and 68% vs. 32%, $p < .05$ for non-fencers. Consistently with our previous study (Przybyla et al., 2013), the non-fencers also reached more often with the right arm for some targets in the left region of space (see Figure 6A: targets C4, D4) or showed almost no preference in arm choice (targets B4, D3). Interestingly, the pattern of arm choice was substantially different for the fencer group. The right arm reaches in fencers were less than in non-fencers for both the middle, 6.5% vs. 23.5%, $p < .05$, and the left region of the workspace, 68.5% vs. 91.5%,

$p < .05$. In fact, fencers did not reach any target in the left region using their right arm more than 50%.

Overall, the group difference in the pattern of arm selection suggests that arm selection asymmetries when reaching to targets across the workspace, corresponds to arm performance asymmetries. Furthermore, it appears that long-term practice of fencing at an elite performance level is associated with more symmetric patterns of arm performance and arm selection.

Discussion

In this study, we examined whether elite fencers and non-fencers might show differences in limb performance asymmetries during simple reaching tasks, and if so, whether these correspond with group differences in arm selection preferences. This design was inspired by our main hypothesis that arm selection asymmetries result from arm performance asymmetries for a given task. We expected that long-term intense training focused on the right-dominant arm might increase limb performance asymmetries during reaching tasks, preferentially biasing the right arm. Second, we predicted that arm selection patterns might be modified in a corresponding manner. Similar to findings reported in previous studies (Coelho et al., 2013; Gabbard & Helbig, 2004; Przybyla et al., 2013), our non-fencers group showed significant interlimb asymmetries, such that right arm reaches were straighter and more accurate to targets across the workspace. In accord with these performance differences, non-fencers selected their right arm significantly more than the left arm. However, our fencer group demonstrated more symmetric patterns of arm performance that were associated with substantially better accuracy and quality of movement in the left arm. In accord with greater symmetry in arm performance, arm selection patterns were significantly more symmetric in the fencer group.

Does fencing improve non-dominant arm performance?

In general, superior motor performance during simple motor tasks for athletes and musicians over non-elite performers has previously been reported (Davlin, 2004; Ramsay & Riddoch, 2001; Rodrigues, Loureiro, & Caramelli, 2013; Sleivert, Backus, & Wenger, 1995). With regard to fencing, greater performance of the right arm in fencers over non-fencers has been reported for discriminative reaction time tasks (Chan et al., 2011; Di Russo, Taddei, Apnile, & Spinelli, 2006). However, the left arm was not assessed in these studies. Although the left arm in fencing is used to help maintain balance and to facilitate attack (Evangelista, 1996), the right arm is practiced extensively to wield the weapon. We therefore expected selectively better performance in only the right arm, as compared with non-fencers. Indeed our fencer group did show a trend toward straighter trajectories and better accuracy for the right arm, compared with non-fencers. However, these differences were not significant. Instead, the fencer group showed substantially straighter and more accurate movements of the left arm when compared with the left arm of non-fencers. While this appears inconsistent with the observation that fencers focus on right arm training, it is possible that this training draws on control processes in each hemisphere, thus influencing performance of both arms. Whether fencers are less asymmetric because of practice in fencing or whether symmetry in

performance is associated with an implicit advantage that might influence competitive selection for fencing cannot be conclusively addressed with the current study design.

Arm selection in fencers and non-fencers

Our results indicated that fencers reached across midline with the right arm significantly less than non-fencers, and that fencers reached with the left arm significantly more than non-fencers. These findings confirm previous studies that indicate that arm selection varies with arm performance under different sensorimotor conditions (Przybyla et al., 2013), and in different groups that show different patterns of performance asymmetry, such as patients with mild hemiparesis (Mani et al., 2013). Interestingly, a previous study of right-handed judo sportsmen suggested that these athletes do show reduced asymmetry in hand preference, as indicated by handedness questionnaire, when compared to non-athletes (Mikheev et al. 2002). These results, however, could be explained by more bilateral demands on athletes in judo, as compared to more unilateral motor demands in fencing. Whereas athletes in judo use both arms to throw and takedown an opponent, fencers use only one arm to perform fast and pointing actions toward the opponent with the weapon. Nevertheless, our current findings indicate that fencers also show reduced asymmetry in hand preference, even though fencing and judo require quite different demands for use of each arm. It is not known whether the group differences in arm performance and selection reported here might result from engagement in elite athletics, or whether self selection or competitive selection for elite fencing might be enhanced by arm performance symmetry.

Is there a competitive advantage of upper limb symmetry for fencing?

The question of whether reduced arm performance asymmetry could represent an implicit advantage for fencing is fascinating. Over the past few decades, we have evaluated the potential processes that might give rise to handedness by combining empirical studies in healthy individuals (Sainburg, 2000; 2002; 2004), computational modeling (Yadav & Sainburg, 2011; 2014), and lesion studies in stroke patients (Mani et al., 2014; Mutha, Haaland, & Sainburg, 2013; Schaefer, Mutha, Haaland, & Sainburg, 2012). This research has led to a model of motor lateralization that attributes different aspects of motor control to the two different brain hemispheres. Our results have converged to support the proposition that two aspects of control are combined in each limb to produce smooth, efficient, and robust movements: 1) impedance control that specifies stiffness-like and viscous-like behavior in the arm and is robust to mechanical variations and perturbations, and 2) predictive mechanisms that are energetically efficient and can result in precise specification of arm trajectories, but are not robust to perturbations.

This model of motor control suggests that optimal performance of either arm should be facilitated through bilateral hemispheric recruitment. In fact, this idea is partially supported by studies of another lateralized behavior, memory recall tasks. Cabeza (2002) has shown consistent evidence that for certain memory functions that are associated with asymmetric patterns of recruitment in young subjects, older subjects tend to recruit more symmetric patterns of prefrontal cortex activity. Importantly, these patterns are associated with better performance on recall, when compared with older adults who do not recruit bilateral brain activity. Cabeza's model has been extended to motor performance. A number of studies have

revealed more symmetric patterns of motor behavior (Chua, Pollock, Elliott, Swanson, & Carnahan, 1995; Przybyla, Haaland, Bagesteiro, & Sainburg, 2011) and interlimb transfer of motor learning (Wang, Przybyla, Wuebbenhorst, Haaland, & Sainburg, 2011) in older adults, while Mattay et al. (2002) have shown that older adults show an increase in bilateral hemispheric recruitment during simple motor behaviors. Thus, evidence in older individuals suggests that more symmetric hemispheric recruitment may be associated with better performance on lateralized tasks, and more symmetric performance on motor tasks. Unfortunately, similar studies have not yet been done in young individuals who show more symmetric patterns of motor performance. It is plausible that such individuals might demonstrate performance advantages, compared with young healthy individuals who recruit more asymmetric patterns of brain activity. We suggest that such advantages might lead to self and competitive selection advantages for elite athletics focused on upper extremity coordination, such as fencing. In fact, it has been well established that there is an increased incidence of left-handers in fencing (Bisiacchi, Ripoll, Stein, Simonet, & Azemar, 1985). Left-handers, in turn, tend to demonstrate more symmetric arm movements (Przybyla et al., 2012). However, the most accepted rationale for the higher incidence of left-handers in tennis and fencing is a game-theory based negative frequency effect (Loffing, Hagemann, & Strauss, 2012). That is, because of the higher incidence of right-handers, players learn a bias through training with right-handed opponents. It should be stressed that all of the fencers in the current study were right-handed, and would not benefit from such negative frequency bias. Instead, these fencers demonstrate reduced lateralization in both motor performance and arm selection. While this may appear surprising, fencing is a sport in which impedance control is required to deal with the opponent's unpredictable interactions, while predictive control is required to specify trajectories for the weapon. Our previous research suggests that these two processes are specialized in different hemispheres, and expressed differentially in the dominant and non-dominant arms. For fencing, it would be advantageous for the dominant arm to access both processes, requiring more symmetric access of each arm to both hemispheres. We propose that in our group of fencers, reduction in arm selection and arm performance asymmetry might be associated with better access of each arm to both hemispheres.

However, it must be noted that this interpretation seems in contradiction with the findings of Semprini et al. (2012), a study that compared estimates of inter hemispheric transfer times during visual motor responses in fencers and non-fencers. The results indicated no main effect of transfer time, but an increase in “crossed-uncrossed differences” in fencers, compared with non-fencers. This measure is also thought to reflect interhemispheric transfer time, and to be an indicator of the integrity of the corpus callosum. These findings suggest an increased reliance on intrahemispheric circuitry, a finding that seems inconsistent with our results. It should be stressed, however, that longer CUD have been associated with reduced handedness (Corballis, 2002), a finding that is consistent with the reduced asymmetries in fencers reported here. It is plausible that in people with reduced handedness, such as fencers, each hemisphere might contain circuitry to control both prediction of dynamics and impedance control. Indeed, Wada testing has revealed that some individuals show dual hemisphere representation for “dominant” language function, such as lexicon and semantic functions (Leherley et al., 2000). However, this explanation is difficult to integrate

with the findings that patients with unilateral sensorimotor stroke seem to lose the lateralized control mechanism associated with the damaged hemisphere, and do not seem to be able to regain that function using the intact hemisphere. At least in those individuals, it is unlikely that both hemispheres mediate both processes. Given the current findings, it is not possible to disentangle these alternative explanations, which would require experiments that include longitudinal as well as neural imaging approaches.

Our current findings unequivocally demonstrate reduced performance asymmetries, and reduced arm selection asymmetries in young adult elite fencers. It is plausible that this asymmetry reduction is related to training, which stresses access of both dominant and non-dominant hemisphere processes for control of dynamics and control of impedance, respectively. The combat nature of fencing would require both of these processes are optimized for single, dominant arm control. It must be stressed that this proposition is highly speculative and requires substantial research to validate or reject.

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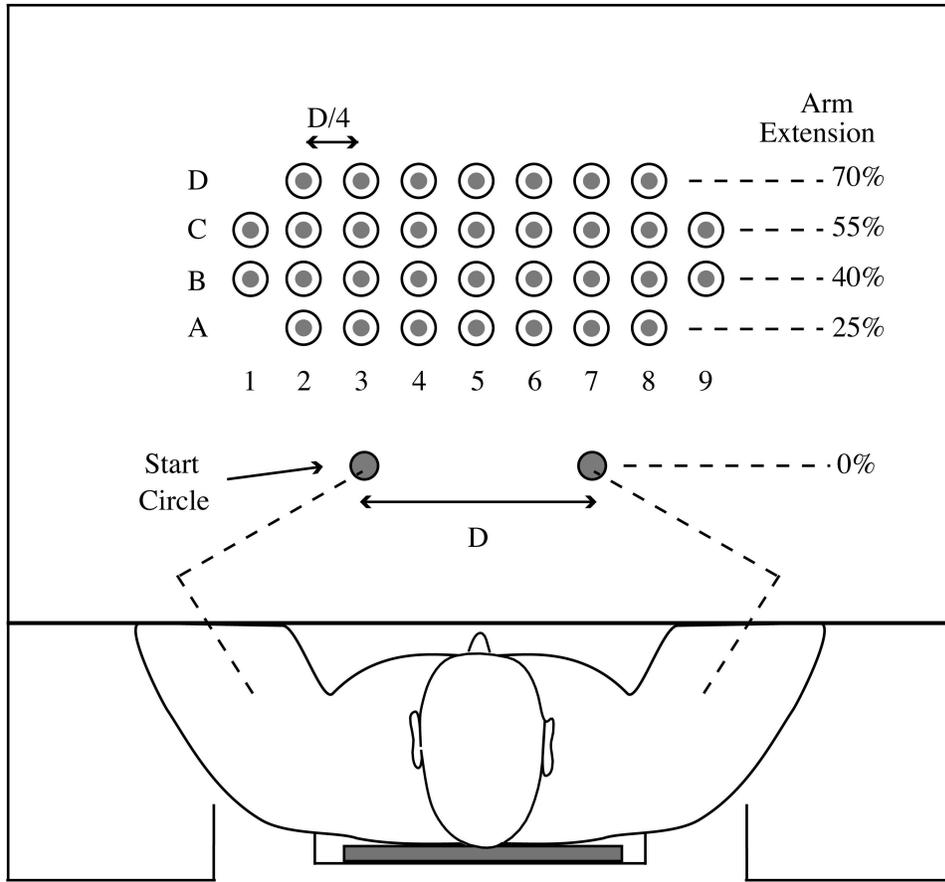


Figure 1.

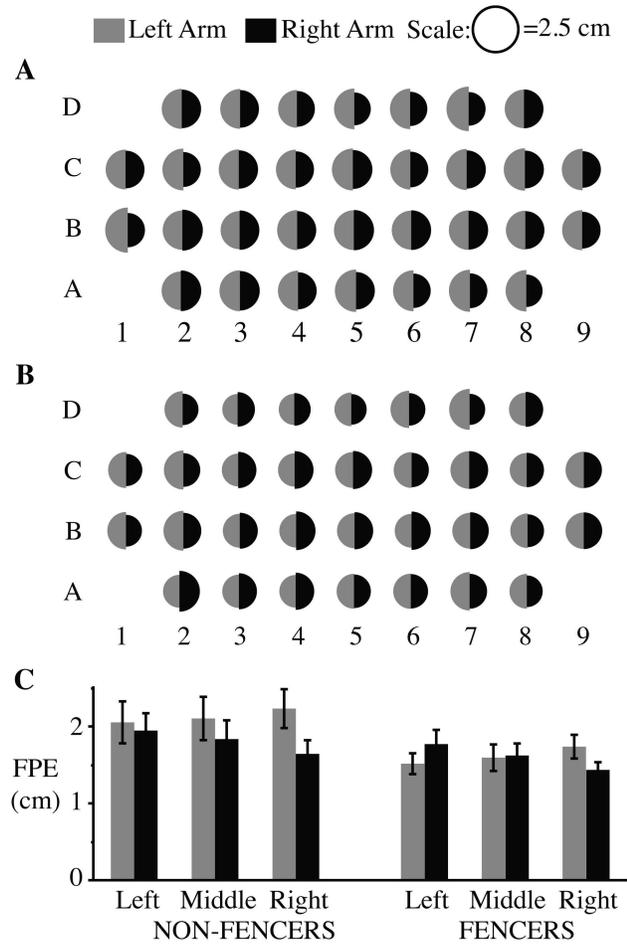


Figure 2.

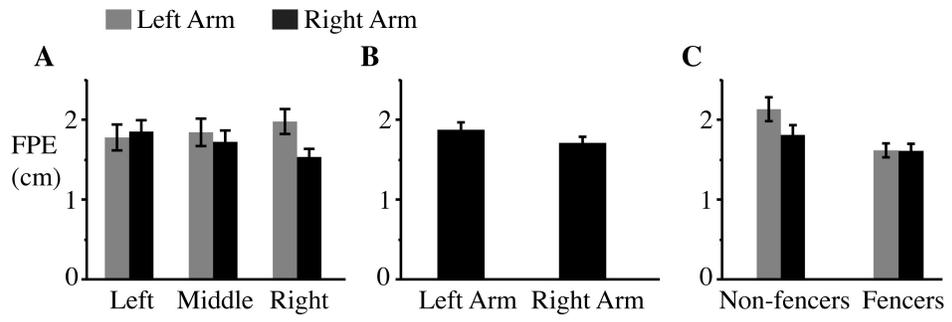


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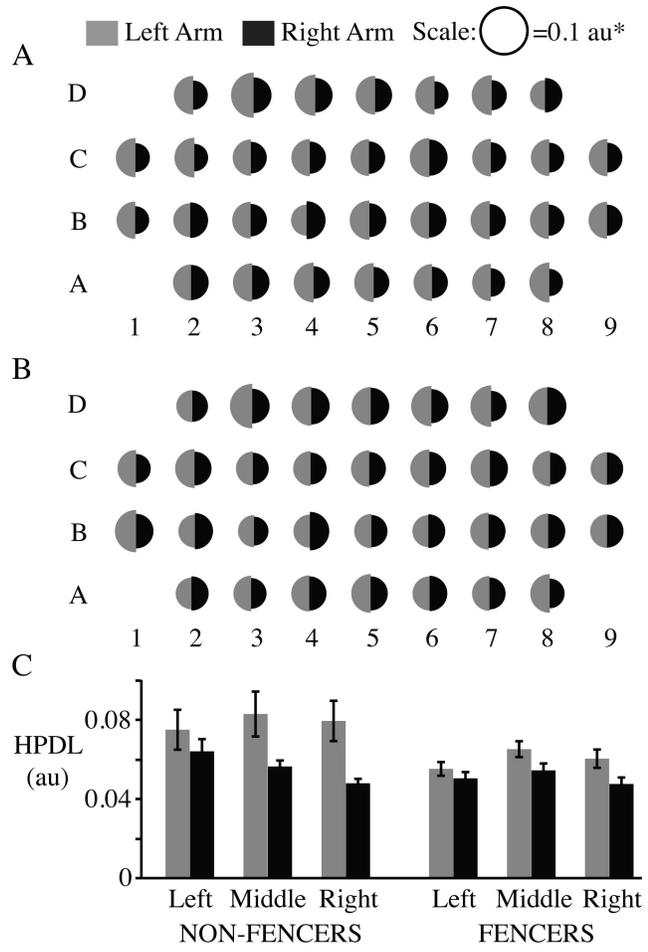


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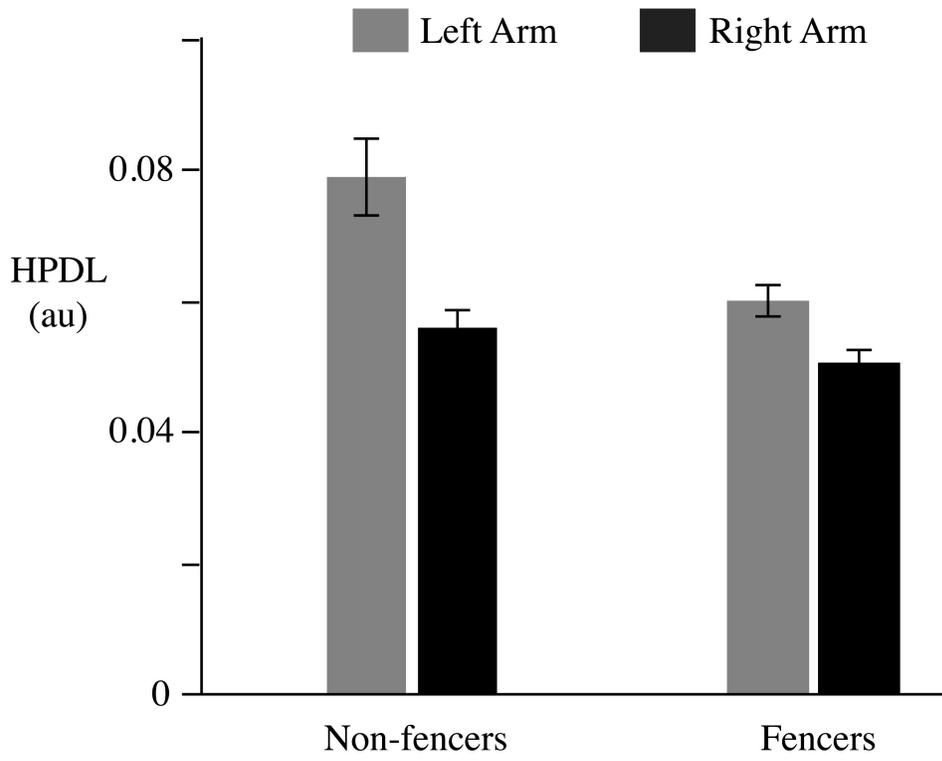


Figure 5.

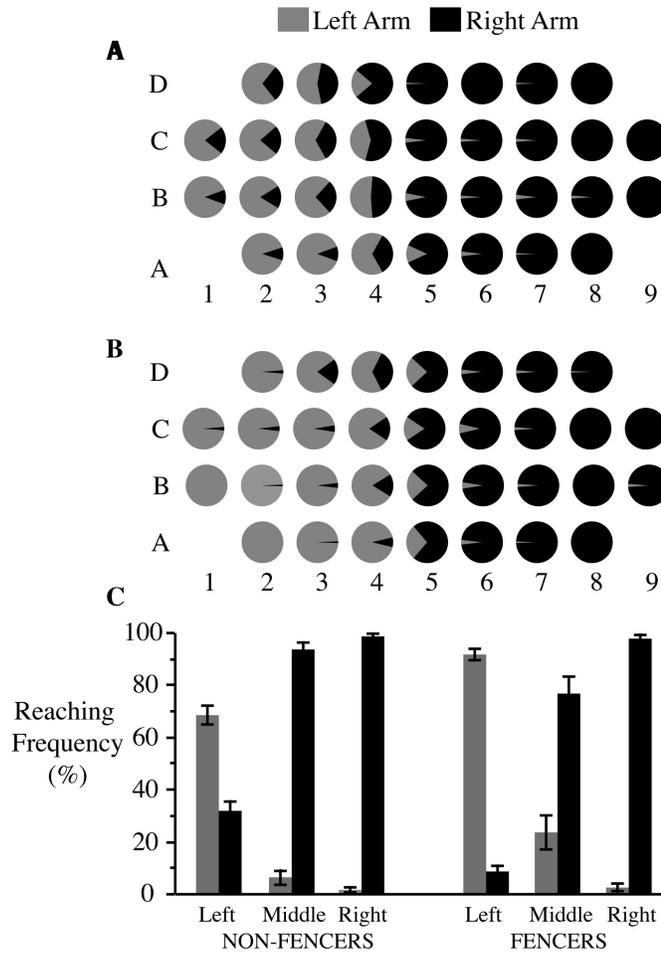


Figure 6.