ISOLATERAL KINETIC INDICES IN THE FIRST SUB MOVEMENT STAGE OF RAPID GOAL-DIRECTED ARM MOVEMENTS

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Abstract
The aim was to explore lateral differences between mechanical energy, power and other kinetic indices in the initial phase of a discrete goal-directed rapid aiming task, based on a speed-accuracy tradeoff. Twenty two young, healthy, right handed males participated in the experiments. Participants were naive to the purpose of the experiment, and none reported any sensory or motor deficits. Left and right arms were tested in separate sessions on the same day. Participants were instructed to move a joystick forward as quickly and accurately as possible towards a target. A computer program selected only the first sub movement with the greatest acceleration and deceleration. Each participant performed 5 series of 10 discrete movements separately with each arm in each situation (100 movements altogether). Force, acceleration, speed, distance and direction were recorded and impulse of force, relative spatial error, power and energy expenditure were calculated. The results demonstrated that the driving forces, mechanical energy, expenditures and power of motions in the initial sub movement of rapid goal-directed arm movements was generally greater from the left, subdominant arm. In accord with the findings of other authors, these results also suggest that distinct neural control mechanisms are employed for even the initial phase of the action of dominant and non-dominant arm movements.

Key words: asymmetry, handedness, neural control, goal-directed

Introduction

All goal-directed reach movements comprise an initial force to ward the target, the primary initial sub movement, and then a late corrective fine tuning, the secondary sub movement near the target (Keele, 1968; Meyer, Abrams, Kornblum, Wright, & Smith, 1988; Milner, 1992). Rapid online control is the important factor (Bernstein, 1967; Rozenbaum, 2010; Schmidt & Lee, 2005) that can improve the quality and effectiveness of performance of fast goal-directed aiming movements to visual targets. This first impulse of the goal-directed movement seems to be more powerful and energetic. It is known that with practice a performer is able to reduce the trial-to-trial variability associated with goal-directed movement through more consistent movement planning processes and more rapid online control. Some authors, who have studied speed-accuracy relations and limb control, concluded that optimization of the speed and accuracy of performance also combines with diminishing energy expenditure (Hansen & Grierson, 2009). A common feature of the models of Elliott and coworkers (2009) is the role of training in optimizing speed, accuracy, and energy expenditure in goal-directed aiming. Training enables individuals to maximize movement speed while minimizing error and energy expenditure. Traditional thought has been that speed-accuracy relations in goal-directed manual aiming are a result of concession between a rapid aiming movement, and the time demanding nature of corrective submovements that are necessary when the initial (primary) submovement trajectory takes the limb outside target boundaries (Meyer et al., 1988). It has been shown that end point distribution of rapid aiming movements depends on energy expenditure costs associated with undershooting or overshooting the target position with the initial pulse (Elliott et al, 2009). Nelson (1983) and Alexander (1997) proposed that an important influence on execution of movement of these gment could have been due to deployment of an energy minimization mechanism. As has been previously demonstrated on the model of locomotion, the most comfortable mode of motor coordination appears to be closely related to responses that involve the lowest energy costs (Lay, Sparrow, Hughes, & O’Dwyer, 2003; Sparrow, 1983). Thus it appears that energetic efficiency and optimization of resources are normally important features of motor skills and maybe these energy and effort minimizing processes are inherent properties of the human motor system (Oliveira, Elliott, & Goodman, 2005; Todorov, 2004). There are many studies that suggest cardinal differences in the control of numerous aspects of movement between arms, mainly in right-handed young people (Bagesteiro & Sainburg, 2002; 2003; Haaland, 2006; Haaland & Harrington, 1996; Haaland, Prestopnik, Knight & Lee, 2004; Sainburg, 2002; 2005; Sainburg & Kalakanis, 2000; Sainburg & Schaefer, 2004). The right hand, dominant in the vast majority of people, seems to be more coordinative and trained.
It may be due to the left hemisphere being more specialized for open loop processing or movement preplanning, which is a component of motor programs (Haalandetal., 2004). It was previously proved that for goal-directed success, the left hemisphere is more specialized for ballistic movements. These ballistic actions are more dependent on planning and less dependent on direct sensory feedback (Haaland & Harrington, 1994). Thus, the left hemisphere plays an important role in controlling various motor skills when greater predominant programming is required (Kim, Gabbard, Ryu, & Buchanan, 2007; Hermsdörfer, Ulrich, Marquardt, Goldenberg & Mai, 1999; Schuler, Krams, Rushworth & Passingham, 2001). Besides, it has been shown that the dominant arm hemisphere system is specialized in the feed for ward control of trajectory, where as the non-dominant arm hemisphere system is specialized in final positional and proprioceptive feedback control (Sainburg, 2005). Despite the significance of all sub movements in the study of motor behavior and the differences in the control strategies employed by the dominant and non-dominant arm hemisphere systems (Sainburg, 2005), no studies were found to have directly addressed the complex investigation of the kinetic indices that represent mechanical energy expenditure with both arms in goal-directed reaching. From the above mentioned reference sit can be suggested that in fast ballistic movements energy related parameters of movement should also be preplanned. It also appears that if the right arm is more adapted for ballistic movements it probably may produce less energy expenditure, and will demonstrate less mechanical power in these motions. However there is a gap in the motor control literature concerning the difference in energy and power between two arms in the primary initial sub movements in selected goal-directed tasks of arms. Thus the aim was to explore the difference between the mechanical energy and other kinetic indices in a discrete goal-directed rapid aiming task that involves functional movements requiring a speed-accuracy trade off.

Methods

Participants

Participants involved in the experiment consisted of 22 healthy, right handed, untrained males, 18-22 years-old. Their body mass indexes were mainly of the mesomorphic type. Sex of the participants was a criterion because of a documented lower level of effectiveness of motor performance in females than in males in complex motor tasks (Jiménez, Jiménez et al., 2011; Pedersen, Sigmundsson, Whiting & Ingvaldsen, 2003; Rodrigues, Vasconcelos, Barreiros & Barbosa, 2009; Tan & Tan, 1997). The research was approved by the Local Research Committee of the Lithuanian Sport University, Kaunas. Education was provided to and informed consent was obtained from each participant before their entry into the study. The degree of right-handedness was confirmed by the Waterloo Handedness Questionnaire (Bryden,1977; Bryden, Pryde, & Roy, 2000). Participants were naive to the purpose of the experiment, and none of them reported any sensory or motor deficits. Left and right arms were tested in separate sessions on the same day. The first arm tested was alternated across participants.

Procedures

A previously used model of arm reaching toward a target with high speed and accuracy of performance was employed (Poston, Van Gemmert, Barduson & Stelmach, 2009). The latest certified model of the Analyzer of dynamic parameters of human movement™ (patent number 5251, 2005-08-25, Lithuania) was used for the experiment. The setup consisted of an armchair in front of a computer monitor on a table. Two vertically oriented joysticks, one for each hand, were placed on the table in front of the monitor. The position of the joysticks and the target were standardized and permanent throughout the experiment. Participants could move the joysticks, but not the target.

Only one hand was used at a time. Each participant sat comfortably in the armchair around 0.70m away from, and in front of the computer screen which displayed a gray target with a diameter of 6mm. The target was located at the same height as the eyes of the participant. A change of color of the target from grey to red conveyed the need to be prepared for the start of motion, the Ready signal. Color change from red to green indicated the Go signal. The interval prior to the Go signal was a constant 1500msec as recommended by Carlsen and Mackinnon (2010). The computer program selected only the first sub movement with the greatest acceleration and deceleration, thus it was more powerful and energetic (Keele, 1968; Meyere tal, 1988; Milner, 1992). Before each movement the joystick was initially placed on a standard start point. Participants were instructed to move the joystick forward as quickly and accurately as possible. Resistance to motion was negligible. Upon initiation of the motion the participant had no opportunity to correct the error in reaching the target. Each participant performed 5 series of 10 discrete movements separately with each arm in each situation (100 movements altogether). The interval between the signals to the motion within each series ranged from 5 to 10 seconds. The interval between series was 1minute. These periods were important to avoid any type of fatigue. The following data were recorded by the computer: a) The average force (F) of movement in Newtons (N), with resolution ±0.001N; b) The time of development of maximum speed (T) in seconds (sec), with resolution ±0.001sec; c) Mechanical energy (E)in Joules (J), with resolution ±0.0013; d) Mechanical power(P),in watts with resolution ±0.001W; e) Absolute distance (D) moved toward the target in mm, with resolution ±0.1mm, and; f) Absolute spatial error(Δ)of the initial primary movement as the distance from the point of termination of the primary impulsive movement to the center of the target in mm, with resolution±0.1mm.
In addition the following indices were calculated:

a) Impulse of force (I) was calculated as:

\[ I = F \times T \]

and expressed in N sec.

b) Relative spatial error (\( \Delta \% \)) was calculated using the formula:

\[ \Delta \% = \frac{100 \times \Delta}{130} \]

where 130 mm represents the shortest possible distance from the starting point to the center of the target (mm), and the result is expressed in %.

**Analysis**

Initially the individual average values of the selected indices and their standard deviations (\( \sigma \)) for a series of 50 movements separately for each arm of each participant were determined. Then the data was grouped according to the lateral performance of movements, selectively for the left and right arms. Final statistical analysis of the results was by way of the Student’s test for non-uniform distribution and \( \chi^2 \) using the statistical analysis software IBM®SPSS22®.

**Results**

Most of the participants demonstrated similar results; their force, energy and power were significantly greater (\( P < 0.05-0.001 \)) from the left arm (Table 1). Ten of the 22 participants had significantly greater force impulse (\( P < 0.05-0.001 \)) from the left side and only two (Nos. 9, 12) from the right side. The other 10 participants demonstrated no significant difference between left and right sides. The majority of people (13 participants) pushed the joystick toward the target using significantly longer distance of primary sub movement from the left arm. However, 4 participants of the 22 (Nos. 6, 7, 16 and 19) pushed the joystick a significantly greater distance with the right hand than the left, and 5 people demonstrated no significant difference in distance between left and right sides (Nos. 3, 12, 14, 15 and 22). The relative spatial error from the left arm was greater than from the right in 8 cases out of 22. In 5 cases (Nos. 1, 9, 11, 21, 22) the spatial mistake from the right hand was greater than from the left, and in 9 cases no significant difference was detected between left and right sides. The \( \chi^2 \) criterion demonstrated unequal distribution of the participant’s capabilities between their arms (\( \chi^2 = 26.279, P = 0.003; \) Table 2).

**Discussion**

The purpose of the study was to discover any difference between mechanical energy and other kinetic indices in a goal-directed rapid aiming task that required a speed-accuracy tradeoff. The computer program selected only the first sub movement.

Twenty-two healthy, young, right handed male participants engaged in the experiment. A large difference between the two arms was evident in terms of applied force, power and energy expenditure. It was interesting that the non-dominant arm usually produced a greater force in goal-directed movement. This finding is in accord with results from other authors who found that non-dominant arm movements were characterized by greater elbow and lower shoulder muscle torques (Sainburg & Kalakanis, 2000). According to Sainburg and Kalakanis the central neural system develops internal models of the applied forces that are used to predict required musculoskeletal and environmental dynamics for preplanning movements. As is also known any muscle training can moderate performance in terms of organization of more consistent planning processes for the required future movements. Because the right, dominant, hand is more trained than the left it may be suggested that training of the muscles of the dominant arm may improve neural efficiency; and lessen brain activity or to diminish the number of motor units recruited for a specific motor action thus reducing metabolic cost (Huang, Kram & Ahmed, 2012). For the goal-directed reaching task the participants produced relatively fast, ballistic movements. It is known that the right arm (left hemisphere) is more specialized for ballistic movements that are more dependent on planning and less dependent on direct sensory feedback (Haaland & Harrington, 1994). The participants performed predominantly simple, single joint, goal-directed tasks which are usually based on bi- or triphasic patterns of muscle activity (Brown & Cooke, 1981; Hallett, Shahani & Young, 1975). Nervous commands in the form of feed-forward alternating bursts of requirements for activity are sent down to the agonists, the muscles that produce the positive torque in the shoulder and elbow joints, and antagonist muscles, the muscles corresponding with negative torque (Brown & Cooke, 1981; Hallettetal., 1975). Thus, antagonists, opposing agonists, will diminish the resulting driving force. This pattern is typical of ballistic action for which right handed muscles are more specialized. According to Meyer and co-workers’ (1998) point of view, an aimed movement toward a specified target region involves a primary sub movement and optional secondary corrective sub movement(s). All submovements are programmed such that they minimize average total movement speed of motion toward the target. This organisation impacts on the amount of kinetic energy. Programming of this type is more appropriate to the left hemisphere. Not all participants performed a longer distance of movement with the left hand. Many researchers have concluded that in each model of motion the central neural system should control movements in a way that minimizes energetic cost (Alexander, 1997; Franklinet al., 2008; Kuo, 2001; Layetal., 2002; McNeill, 2002; Nelson, 1983; Todorov & Jordan, 2002). Experiments by Oliveira and coworkers (2005) demonstrated less energy consumption without reference to the length of motion, overshooting or undershooting targets.
Table 1. Individual results of all the dynamic indices.

<table>
<thead>
<tr>
<th>Participant</th>
<th>F</th>
<th>I</th>
<th>D</th>
<th>Δ%</th>
<th>P</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dom 1</td>
<td>7.90</td>
<td>1.39</td>
<td>102.88</td>
<td>20.87</td>
<td>1.15</td>
<td>0.82</td>
</tr>
<tr>
<td>Non 1</td>
<td>9.57</td>
<td>2.01</td>
<td>107.01</td>
<td>18.01</td>
<td>2.02</td>
<td>1.83</td>
</tr>
<tr>
<td>P</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.01</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Dom 2</td>
<td>6.93</td>
<td>1.20</td>
<td>148.36</td>
<td>19.82</td>
<td>3.17</td>
<td>2.40</td>
</tr>
<tr>
<td>Non 2</td>
<td>8.55</td>
<td>1.43</td>
<td>160.13</td>
<td>25.02</td>
<td>1.25</td>
<td>1.20</td>
</tr>
<tr>
<td>P</td>
<td>&lt;0.001</td>
<td>&lt;0.05</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Dom 3</td>
<td>5.99</td>
<td>1.26</td>
<td>123.84</td>
<td>12.24</td>
<td>1.14</td>
<td>0.85</td>
</tr>
<tr>
<td>Non 3</td>
<td>7.71</td>
<td>1.40</td>
<td>125.28</td>
<td>14.19</td>
<td>2.22</td>
<td>2.09</td>
</tr>
<tr>
<td>P</td>
<td>&lt;0.001</td>
<td>&lt;0.05</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Dom 4</td>
<td>4.40</td>
<td>0.70</td>
<td>116.38</td>
<td>13.10</td>
<td>1.76</td>
<td>1.36</td>
</tr>
<tr>
<td>Non 4</td>
<td>6.55</td>
<td>0.69</td>
<td>119.96</td>
<td>12.07</td>
<td>1.64</td>
<td>1.40</td>
</tr>
<tr>
<td>P</td>
<td>&lt;0.001</td>
<td>&lt;0.01</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Dom 5</td>
<td>5.51</td>
<td>0.91</td>
<td>123.95</td>
<td>14.33</td>
<td>1.20</td>
<td>1.06</td>
</tr>
<tr>
<td>Non 5</td>
<td>9.59</td>
<td>1.69</td>
<td>144.01</td>
<td>13.05</td>
<td>3.30</td>
<td>2.29</td>
</tr>
<tr>
<td>P</td>
<td>&lt;0.001</td>
<td>&lt;0.05</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Dom 6</td>
<td>6.52</td>
<td>1.32</td>
<td>132.55</td>
<td>14.84</td>
<td>1.08</td>
<td>0.92</td>
</tr>
<tr>
<td>Non 6</td>
<td>7.29</td>
<td>1.41</td>
<td>129.93</td>
<td>15.36</td>
<td>2.14</td>
<td>1.90</td>
</tr>
<tr>
<td>P</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Table 2. The distribution of participants according to their lateral performances.

<table>
<thead>
<tr>
<th>Indices</th>
<th>F</th>
<th>I</th>
<th>D</th>
<th>Δ%</th>
<th>P</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left &gt; Right</td>
<td>18</td>
<td>10</td>
<td>13</td>
<td>8</td>
<td>16</td>
<td>18</td>
</tr>
<tr>
<td>Left = Right</td>
<td>0</td>
<td>10</td>
<td>5</td>
<td>9</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Left &lt; Right</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>sum</td>
<td>22</td>
<td>22</td>
<td>22</td>
<td>22</td>
<td>22</td>
<td>22</td>
</tr>
</tbody>
</table>

Legend: Dom – the right, dominant arm; Non – the left, non-dominant arm; F – Force in Newtons; I – Impulse of force in Nsec; D – Absolute distance moved toward the target in mm; Δ% - Relative spatial error in %; P – Power in watts; E – Energy in joules.
The authors suggested that the so-called energy minimization mechanism might be inherent to biological systems. It seems that this possible mechanism is more appropriate to the dominant hand, probably because its muscles are more trained. Other researchers have stressed the role of practice (training) in optimizing speed, accuracy, and energy expenditure in goal-directed aiming movements (Elliott, Hansen, Mendoza, & Tremblay, 2004). Training of the right arm in every day practice is more pronounced than the left and this may explain why the right arm is working more economically than the left. The level of accuracy from the left side in many trials was greater in comparison to the right. An explanation of this observation is that the right hemisphere controls mostly spatial patterns of movement. Previous researchers have revealed a possible superiority of non-dominant arm control for final position accuracy (Bagesteiro & Sainburg, 2002; Sainburg & Wang, 2002). Eleven participants of the 22 demonstrated a greater force impulse from the left arm, but another 10 participants demonstrated no significant difference between the two arms. Force impulse is comprised of the magnitude of applied force and the time of motion performed under the force. Increased time of action under tension of muscles, when the force is acting longer, may be treated as a positive characteristic stimulating training and muscle adaptation (Wesscottetal, 2001). Some other authors have demonstrated that the magnitude of mechanical stress is more responsible for strength gains and muscle hypertrophy (Dudley, Tesch, Miller, & Buchanan, 1991; Hortobagyi etal, 1996). Probably both factors play a role in the adaptation of muscles of dominant and non-dominant arms to create energetically effective movements. These reasons likely explain why no clear pattern was observed for the force impulse recorded from the left and right arms.

Conclusions

This study demonstrated that the driving forces, mechanical energy expenditures and power of the initial sub movement of rapid goal-directed arm movements was generally greater from the left, non-dominant arm. According to the findings of other researchers, these results also suggest that distinct neural control mechanisms are employed for dominant and non-dominant arm movements even during the initial phase of action. For future investigations it is recommended that specific exercises measuring energy expenditure are included in the battery of arm testing techniques.

References


Sažetak
Cilj je bio istražiti lateralne razlike između mehaničke energije, snage i ostalih kinetičkih indeksa u početnoj fazi diskretno cilju usmjerenih akcija, temeljeno na promjeni brzina-točnost. Dvadeset dva mlada, zdrava, muškarca dešnjaka sudjelovalo je u eksperimentu. Sudionici su bili neiskusni u smislu pokusa, i nitko prijavio bilo senzorne ili motorne deficite. Lijeve i desne ruke su testirane u odvojenim sesijama na isti dan. Sudionici su dobili upute da premjestite joystick prema naprijed što je brže i točnije moguće prema cilju. Računalni program bira samo prvi pod-pokret s najvećim ubrzanjem i usporavanjem. Svaki sudionik izvodio je 5 serija od 10 diskretnih pokreta zasebno s obje ruke u svakoj situaciji (100 pokreta uopće). Snaga, ubrzanje, brzina, udaljenost i smjer zabilježeni su a impuls sile, relativna prostorna pogreška, snaga i potrošnja energije su izračunati. Rezultati su pokazali da su pokretačke snage, mehanička energija, rashodi i moć pokreta u početnoj fazi pod-kretanja brzih ciljno usmjerenih pokreta desne ruke bili općenito bolji od lijeve, subdominantne ruke. U skladu s nalazima drugih autora, ovi rezultati sugeriraju da su različite neuronski mehanizmi kontrole aktivni čak u početnoj fazi djelovanja pokreta dominantne i nedominantne ruke.

Ključne riječi: asimetrija, nespretnost, neuralna kontrola, ciljno usmjerenost