Comparison of Modular Control of Trunk Muscle by Japanese Archery

Competitive Level: A pilot study

Modular Control of Trunk Muscles During Japanese Archery

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ABSTRACT

This study investigated modular control during Japanese archery and compared the modules between an elite group (level 4 or above in the Kyudo proficiency test) and a novice group (level 3 or lower) in a pilot study. Muscle activities were recorded on both sides of the rectus abdominis, external oblique (EO), internal oblique/transversus abdominis (IO/TrA) and erector spinae (ES) using surface electromyography. Modules were extracted from electromyography signals using non-negative matrix factorization (NMF). According to the results of NMF analysis, two modules explained the electromyographic activity of all muscles. One module was the same between groups.
and consisted mainly of data from the ES muscle during the first half of the shooting sequence. It is considered a means of stabilizing the trunk to keep it from moving during shoulder flexion and abduction motion. The other module was different between groups, although the activation timing was similar. The module in the elite group mainly engaged IO/TrA activity. In contrast, the module in the novice group mainly comprised EO activity. The IO/TrA fixes the trunk during upper limb movement in the upright position. This result suggests that IO/TrA activity during the shooting sequence may influence performance.

Keywords: Muscle synergy, module, non-negative matrix factorization, sports performance
INTRODUCTION

The degrees of freedom in human voluntary movement are high; for instance, in a reaching task, there are countless trajectories to the object and combinations of joint angles with respect to trajectories, as well as combinations of muscle tensions corresponding to the joint angles. The central nervous system (CNS) selects one movement from these countless options (Figure 1). However, the mechanism by which the CNS controls the muscles involved in these movements remains unclear. One of the theories on how the CNS controls movement infers that movements to a large extent are controlled by a combination of a few basic activation patterns, also known as motor modules or muscle synergies (Bernstein, 1967). A muscle synergy can be characterized as a low-dimensional organizational structure controlling multiple muscles. The muscle synergy can be identified from electromyographic (EMG) patterns recorded from numerous muscles via an algorithm with two components: “muscle weighting”, which represents the relative weighting of each muscle within each module; and the “activation coefficient”, which represents the relative activation of the muscle weighting (Hug et al., 2010; Turpin et al., 2011; van den Hoorn et al., 2015) (Figure 2). Conventional EMG analysis can clarify the percentage of muscle activity, timing of onset, and fatigue using frequency analysis (Nishizono. 2004). On the other hand, muscle synergy is extracted by non-negative matrix factorization (NMF) analysis and it can clarify the muscle coordination in each function by grouping movements according to their function (Torricelli et al., 2016).

Kottke et al. (1978) used muscle synergy analysis for rehabilitation, but in recent years this has also been applied to sports, and the relationships between muscle synergy and sports performance or injuries have been studied. It is reported that the “muscle
weighting” factors are different, depending on the competition level; muscle weighting was evaluated in studies on rowing exercise and walking (Turpin et al., 2011; Sawers et al., 2015). These results indicate that the contributions of muscles mobilized when performing the same voluntary movement is different, most likely due to long-term training and improvement of competition level. The muscle weighting factors during breaststroke swimming are not different; however, the activation coefficient factors are different, depending on the competition level (Vaz et al., 2016). From these reports, it can be said that muscle synergy influences the sports performance level. Kyudo, or Japanese archery, has fewer degrees of freedom than other sports because the main movements in Kyudo involve the upper limbs, while the trunk and lower limbs remain fixed; thus, the muscle synergy may be different depending on the competition level. In Kyudo, the movements to draw a bow are divided into 8 paragraphs called “Syahouhassetsu” (Inagaki, 1997). Syahouhassetsu is especially involved in the no-movement paragraphs while “ashibumi” and “douzukuri” are concepts used to stabilize the trunk, and are also important to improvement in Kyudo performance. However, most studies on Kyudo have only focused on the upper limbs (Kamei et al, 1971; Yamada, 1991; Konishi and Fujiwara, 2005), and no study has focused on the trunk muscles. The transversus abdominis (TrA) is located deep within the trunk muscle group and activates to assist in postural control during upper limb elevation on standing (Crommert et al., 2011). Recently, trunk stabilization exercises that focused on the deep trunk TrA and multifidus muscles have been recommended to improve sports performance and prevent injuries (Imai et al., 2014; Soligard et al. 2008; 2010). TrA activity may be the important factor determining performance in Kyudo. Thus, the purpose of this study was to investigate whether muscle synergy is different depending
on the competition level. We hypothesized that the TrA activity in elite, competition-
level players is high, and that muscle synergy, which is a major component of TrA, can
be extracted. Clarification of posture-maintaining muscle functions using NMF may be
useful for Kyudo players and coaches, for emphasis on training to enhance muscle
coordination in accordance with Kyudo competition.

METHODS

Nine healthy men (age: 22 ± 1 years, height: 1.70 ± 0.05 m, weight: 65.2 ± 9.0 kg,
competition history: 7 ± 3 years) participated in this study. All performed Kyudo
training once or twice a week. The subjects were divided into an elite group and a
novice group. The elite group had obtained level 4 or above on the Kyudo proficiency
test, while those in the novice group were at level 3 or below. Four subjects were
included in the elite group. This study was approved by the ethics committee of our
university. All subjects provided informed consent to participate in the study.

After subjects performed several practice shots, the EMG equipment was set up, and
muscle activity during the shooting sequence was measured. Subjects faced a target to
perform 4 shots. The target, with a diameter of 0.36 m, was placed at a distance of 28 m
from the subjects. We analysed the 2 best shots that hit the centre of the target. The
activities of the trunk muscles were measured using a wireless EMG telemetry system
(EMG-025, Harada Electronics Industry Ltd., Sapporo, Japan) at 1,000 Hz. Before the
surface electrodes were attached, the skin was rubbed with a skin abrasive and alcohol
to reduce impedance to a level below 2,000 Ω. Paired, 3×2 cm disposable Ag/AgCl
surface electrodes (BlueSensor N-00-S, METS Co., Adachi, Japan) were attached
parallel to the muscle fibres, with a centre-to-centre distance of 2 cm. The rectus
abdominis (RA) electrode placement was 3 cm lateral to the umbilicus. The external oblique (EO) electrode placement was midway between the costal margin of the ribs and iliac crest, approximately 45 degrees to horizontal. The internal oblique/transversus abdominis (IO/TrA) electrodes were placed approximately 2 cm medial and inferior to the anterior superior iliac spine, and the erector spinae (ES) electrodes were placed 3 cm lateral to the L4 spinal process. Prior to measurement, subjects performed maximum voluntary contraction (MVC) tests using manual resistance to normalize the EMG data. The MVC for the RA was obtained as the subjects performed a partial sit-up with their knees flexed and manual resistance applied. For the EO on the right side and IO/TrA on the left side, the subjects were in a supine position, with knees flexed and trunk flexed and rotated to the left. Resistance was applied at the shoulders in the trunk extension and right rotation directions. For the EO on the left and IO/TrA on the right side, the trunk was instead flexed and rotated to the right, with the resistance applied at the shoulders in the trunk extension and left rotation directions. For the ES, the MVC task was trunk extension performed in the prone position with application of manual resistance to the upper thoracic area and without leg movement. Manual resistance was gradually increased up to the subject’s limit, then held for 3 s. To monitor the start and end of the trial, a video camera (EX-FH25, CASIO COMPUTER CO., LTD. Shibuya, Japan) recording at 240 Hz was set in front of the subjects and was synchronized with the EMG system. EMG data analysis software (BIMUTAS-Video, Kissei Comtec Co, Ltd. Matsumoto, Japan) was used. First, the raw EMG data were band-pass filtered (20 to 450 Hz) and full-wave rectified. Second, the root-mean-square during MVC was calculated and was used to normalize the EMG data. After that, we extracted EMG data for a shooting cycle.
using video data. Data for each shooting sequence were interpolated to 200 time points using MATLAB (MATLAB R2016, MathWorks, Inc., Natick, MA, USA). Then, as previously described, NMF was performed to extract muscle synergies based on a study by Lee and Seung (2001), given as:

\[ E = W \cdot C + e \quad \text{(formula 1)} \]

\[ \min_{W \geq 0, C > 0} \| E - WC \|_{FRO} \quad \text{(formula 2)} \]

where, \( E \) is a \( p \)-by-\( n \) initial matrix (\( p \) is number of muscles and \( n \) is number of time points). The initial matrix comprised normalized EMG data, and consisted of a cycle for each of the 8 muscles; therefore, \( E \) was a matrix with 8 rows and 200 columns. \( W \) is a \( p \)-by-\( s \) matrix (\( s \) is the number of synergies) which includes that \( s \) number of muscle weighting; \( C \) is an \( s \)-by-\( n \) matrix, and represents the activation coefficient; and \( e \) is a \( p \)-by-\( n \) residual error matrix. Formula 2 indicates that matrix “\( e \)” calculated using formula 1 reaches minimum. For each subject, we iterated the analysis by varying the number of synergies between 1 and 8, and then selected the least number of synergies that accounted for \( >90\% \) of the Variance Accounted For (VAF) (Hug et al., 2010; Torres-Oviedo et al., 2006; Hug, 2011). VAF was calculated based on these studies:

\[ \text{VAF} = \left(1 - \frac{\sum_{i=1}^{p} \sum_{j=1}^{n} (e_{ij})^2}{\sum_{i=1}^{p} \sum_{j=1}^{n} (E_{ij})^2}\right) \times 100 \]

where, \( i \) goes from 1 to \( p \) and \( j \) goes from 1 to \( n \). Thus, \( i \) was from 1 to 8 and \( j \) was from 1 to 200 in this study.

To compare \( W \) between both groups, the scalar product (SP) was calculated based on the study by Cheung et al. (2012):
where $\overrightarrow{W_{\text{elite}}}$ and $\overrightarrow{W_{\text{novice}}}$ are defined as $\overrightarrow{W}$ of elite group and novice group, respectively. Each $\overrightarrow{W}$ is averaged vector among subjects in each group.

The SP for the use of correlation coefficients can assess the similarity of $W$. We defined the module as the same if $SP > 0.75$.

7 **RESULTS**

Figure 3 shows representative EMG data for one of the subjects, corresponding to shooting sequence. Figures 4 and 5 show the results of NMF analysis. When there are 2 modules, the VAF exceeds 90% for the first time (*Figure 4*). Therefore, 2 modules were extracted in each group (*Figure 5*). All subjects had 2 modules. The SP of module 1, which indicates the coincidence of muscle weighting, was 0.99; the result indicates that module 1 was the same in both groups. The data from module 1 mainly reflected bilateral ES activity during the first half of the shooting sequence. The activity level of module 1 in the elite group was higher than in the novice group in the second half of the shooting sequence. However, for module 2, the SP was 0.44, indicating that module 2 was different between the groups. Module 2 in the elite group was engaged mainly during IO/TrA activity, while module 2 in the novice group was engaged during EO activity. Although these modules were different, the activation coefficients indicated that module 2 in both groups were highly activated in the second half of the shooting sequence.

7 **DISCUSSION**
This study investigated both sides of trunk muscle activity during shooting. The main findings of this study were that 2 modules were active while shooting and the muscle coordination of module 2 was different between the elite and novice players. Module 1, which mainly engaged the ES, was activated in the first half of the shooting sequence, and this module was the same in both groups (Figure 5). The main movement in this period corresponded to raising the upper limbs and pulling the bow, as in Figure 3. Crommert et al. (2011) reported that the ES activates during upper limb elevation in the upright position, although the activity level is lower than in the TrA. Davey et al. (2002) also reported that the contralateral ES activates during shoulder abduction. From these reports, it is thought that the function of module 1 is to maintain lifting and induce abduction of the shoulders. Additionally, the activity level of module 1 in the elite group in the second half of the shooting sequence was higher than in the novice group. The force produced by fully drawing the bow disappears with release of the arrow, and this changes the load on the body. Moreover, the shoulders must remain in abduction after arrow release, and thus it is thought that the both sides of ES are activated to maintain posture. The individual differences in ES activation in module 1 were greater than in other muscles (Figure 5). Some subjects performed the shooting sequence with the lumbar spine in extension, although trunk motion was not analysed because the video recorder was set in front of the subjects. It is thought that this strategy might produce trunk stability due to muscle function as well as mechanical stability by fixing the lumbar spine at the end of range of motion. Therefore, future research should evaluate trunk stability during the shooting sequence to include lumbar spine motion analysis. The SP for module 2 was low; hence, muscle weighting in module 2 was different between the groups. Module 2 in the elite group engaged IO/TrA, while module 2 in the
novice group engaged EO. It has been reported that the activity of TrA is associated
both with maintaining a balanced upright trunk posture as well as counteracting
imposed flexion moments on the trunk during upper limb elevation movement
(Crommert et al., 2011). Since posture maintenance enhances competitive skills, elite
players activated the IO/TrA to fix the trunk. On the other hand, since module 2 in the
novice group mainly engaged the EO, and since the activity of IO/TrA in the novice
group was low, it is thought that the activity of EO demonstrated increased
compensation. Additionally, local muscles including the TrA, which attach to and
stabilizes the lumbar spine, and global muscles, including the EO, which are not
attached to the lumbar spine, generate a large amount of torque to control dynamic trunk
motion. It is thought that trunk stability due to TrA activity is important, because there
is no dynamic trunk motion during the shooting sequence. Moreover, the individual EO
differences in the novice group were large; this suggests that there are several patterns
of trunk stabilizing strategy in the novice group compared with the elite group.
We compared muscle synergies during the shooting sequence in the elite and novice
groups using NMF. The elite group controlled trunk stability with both sides of the ES
in the first half of the sequence, and both sides of the IO/TrA in the second half.
Recently, trunk stabilization exercise has been recommended to prevent injury and
improve performance in several sports (Imai et al., 2014; Soligard et al. 2008; 2010). It
has been reported that trunk muscle activity during trunk stabilization exercise is
increased with upper or lower limb elevation because exercise intensity increases with
decreasing body support. For instance, TrA activity on the right side in elbow-toe
posture with right arm and left leg lifting is greater than on the left side (Okubo et al.,
2010). Based on our results, it is thought that trunk stability induced by the coordination
of both sides of the TrA is important; therefore, trunk stabilization exercise without upper or lower limb lifting might be useful for improving Kyudo performance.

CONCLUSION

We examined trunk muscle activities during the shooting sequence according to competition level. Players with a high competition level stabilized the trunk with the internal oblique and transversus abdominis. In contrast, the activity of the internal oblique and transversus abdominis was low in novice competition level players, and external oblique activation compensated to stabilize the trunk.
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Figure 1  The degrees of freedom during human voluntary movement
Left: There are orbitals countlessly to the objects.
Center: There are joint angles of upper limb countlessly.
Right: There are muscle tensions to decide the joint angles of upper limb countlessly.
Figure 2  The concept of extracting modules using non-negative matrix factorization. Electromyography data is divided into muscle weighting and activation coefficient using Non-Negative Matrix Factorization (NMF). M1, M2, and M3 indicate muscle name.
Figure 3 One of subjects’ EMG data during Japanese archery bowing and corresponding motion (created by Inagaki (1997))
Solid line: right side muscle Dot line: left side muscle
Figure 4  VAF corresponding to number of modules
The number of module is decided when the VAF exceeds 90% for the first time. In this case, number of modules is decided two. VAF: Variance accounted For
Figure 5  Extracted modules during bowing.
RRA: right side rectus abdominis  LRA: left side rectus abdominis  REO: right side external oblique  LEO: left side external oblique  RIO/TrA: right side internal oblique/transversus abdominis  LIO/TrA: left side internal oblique/transversus abdominis  RES: right side erector spinae  LES: left side erector spinae  SP: scalar product (indicates the similarity between both groups)