Specific muscle coordination patterns of taekwondo roundhouse kick in athletes and non-athletes

Authors' Contribution:
A Study Design
B Data Collection
C Statistical Analysis
D Manuscript Preparation
E Funds Collection

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Abstract

Background and Study Aim: Muscle coordination is defined as the distribution of muscle activation among individual muscles to produce functionally significant movements. To represent muscle coordination patterns during functional movements, muscle synergy is analysed using a non-negative matrix factorization algorithm that decomposes electromyography (EMG) signals into fixed and time-varying components This study aims is knowledge about specific muscle coordination patterns for roundhouse kick in taekwondo athletes.

Material and Method: Eleven athletes and 11 non-athletes participated in this study. To identify muscle coordination patterns, muscle synergies are analysed based on synchronized electromyography (EMG) data with 3D motion captures. Furthermore, clustering analysis is conducted to categorize similar muscle synergies during roundhouse kick in all participants.

Results: As expected, the execution times of the roundhouse kick in the athletes was significantly faster and those of non-athletes. Specifically, the athletes demonstrate an additional co-activation of plantar flexor on the dominant (kicking) leg in the toe-off phase. In the knee flexion phase, the non-athletes demonstrate an extensive co-activation of the dominant leg muscles. In the impact phase, the athletes demonstrate a co-activation of the dominant knee extensors and hip abductor, whereas the non-athletes demonstrate a relatively extensive co-activation of the non-dominant (supporting) leg muscles.

Conclusions: This investigation provides specific strategies of muscle coordination patterns for the roundhouse kick in taekwondo. Our findings provide beneficial information pertaining to specific muscle coordination patterns in athletes, thereby facilitating the development of training strategies for roundhouse kick.

Keywords: elite athlete • muscle synergy • technique

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Elite – *adjective* more talented, privileged or highly trained than others [25].

Athlete – *noun* 1. someone who has the abilities necessary for participating in physical exercise, especially in competitive games and races **2.** a competitor in track or field events [25].

Player – *noun* someone taking part in a sport or game [25].

Skeletal muscle – *noun* a muscle that is attached to a bone and makes a limb move [25].

Nervous system – *noun* the nervous tissues of the body, including the peripheral nerves, spinal cord, ganglia and nerve centres [25].

Synergy – *noun* a situation where two or more things are acting together in such a way that both are more effective [25].

Technique– *noun* a way of performing an action [25].

Roundhouse kick – (in taekwondo terminology referred to as ***dollyo chagi***) has a considerable influence on the final score in a competition [15].

Roundhouse or circular kick – a type of kick defined as throw-like kicks or progressive movements of hip and knee flexion-extension of the kicking leg that start in the sagittal plane and finish in the transverse plane (i.e., swing motion), with the ankle in plantar flexion to hit in lateral body posture with the instep [26].

Roundhouse kick (bandal tchagui) – a type of kick executed to the chest that generally starts in the sagittal plane and finishes in the lateral plane [26].

INTRODUCTION

Muscle coordination is defined as the distribution of muscle activation among individual muscles to produce functionally significant movements [1]. To represent muscle coordination patterns during functional movements, muscle synergy is analysed using a non-negative matrix factorization algorithm that decomposes electromyography (EMG) signals into fixed and time-varying components [2]. In the muscle synergy, the fixed component (or synergy structure) represents the relative weight values of individual muscles within each muscle synergy, and the time-varying component (or synergy activation) represents synergy activation profile, representing the relative contribution of the muscle synergy during a specified task [3].

In sports sciences, a previous study demonstrated that long-term training can change muscle synergies [4-6]. The results of tests with the use of a rowing ergometer are helpful in understanding the importance of anthropometric differences on cardiorespiratory performance, because the synergy factor of muscle work is dominant in such an effort [7, 8]. This is supported by the result of a previous study in which specific muscle synergies were discovered in professional ballet dancers as compared to novice dancers during beam walking [9]. From this point of view, we assumed that athletes-specific muscle synergies would be observed. Those studies support the presence of specific muscle synergies, particularly those produced in athletes. The specific muscle synergies of taekwondo athletes are rarely investigated. In taekwondo competitions, a fast and accurate kick is required to achieve points [10]; therefore, the kick motion of elite athletes require a shorter time [11, 12] and exhibit greater accuracy when compared with those of sub-elites [13-16].

This study aims is knowledge about specific muscle coordination patterns for roundhouse kick in taekwondo athletes.

MATERIAL AND METHODS

Participants

The participants in this study included 11 athletes who were registered as athletes with the Korea Taekwondo Association (11 male; mean age, 21.27 ±1.19 years; body mass, 72.55 ±9.96 kg; height, 72.55 ±9.96 cm) and 11 non-athletes (11 male; mean age 22.91 ±1.62 years; body mass, 75.16±10.49 kg; height 170.0 ±7.99 cm). Exclusion criteria were injury experiences of skeletomuscular and nerve system within three months. We explained the purpose and method of this study to the participants, and the latter provided written consent. The protocol of this study was approved by the Institutional Review Board.

Equipment

All participants completed 12 trials of the roundhouse kick at each of head and weight targets while synchronized EMG (AVANTI, Delsys, USA) and kinematic data (eight motion capture cameras, Prime 13, Optitrack, USA) were collected. The sampling rates of the EMG signals and motion capture systems were set to 1,000 and 100 Hz, respectively. The EMG data were recorded bilaterally from the adductor magnus (AM), rectus femoris (RF), gluteus medius (GM), vastus lateralis (VL), biceps femoris (BF), gastrocnemius (GC) tibialis anterior (TA), and peroneus longus (PL) (Figure 1). EMG signals were examined using manual muscle testing for each muscle. Data were analysed using Visual3D (Visual3D V6 Professional, C-Motion, Germantown, USA) and Python 3.7.3 software.

Procedure

In this study, the roundhouse kick was selected because it is the fastest kick among taekwondo kick techniques [14] and the most frequently used in competitions [17]. For data analysis, EMG was signals were decomposed for muscle synergy extraction using non-negative matrix factorization (NMF), and similar muscle synergies were classified based on clustering analysis. Finally, we defined group-specific muscle synergies based on proportions of two groups within individual clusters.

In the study, we defined dominant and non-dominant legs as kicking and supporting legs in the roundhouse kick, respectively. The head and weight target heights were set to 60% and 85% of each participant's height, respectively. The target distances were defined based on the leg length, and the distance from the anterior superior iliac spine to the medial malleolus. Specifically, the distance of the waist target was as long as the participant's dominant leg length. The distance of the head target was calculated as , where LL is the leg length, and UBL is the distance between the greater trochanter and the head. In the experiment, the participants performed a roundhouse kick to each target as quickly as possible immediately after a visual cue was provided. The task was repeated 12 times for each target.

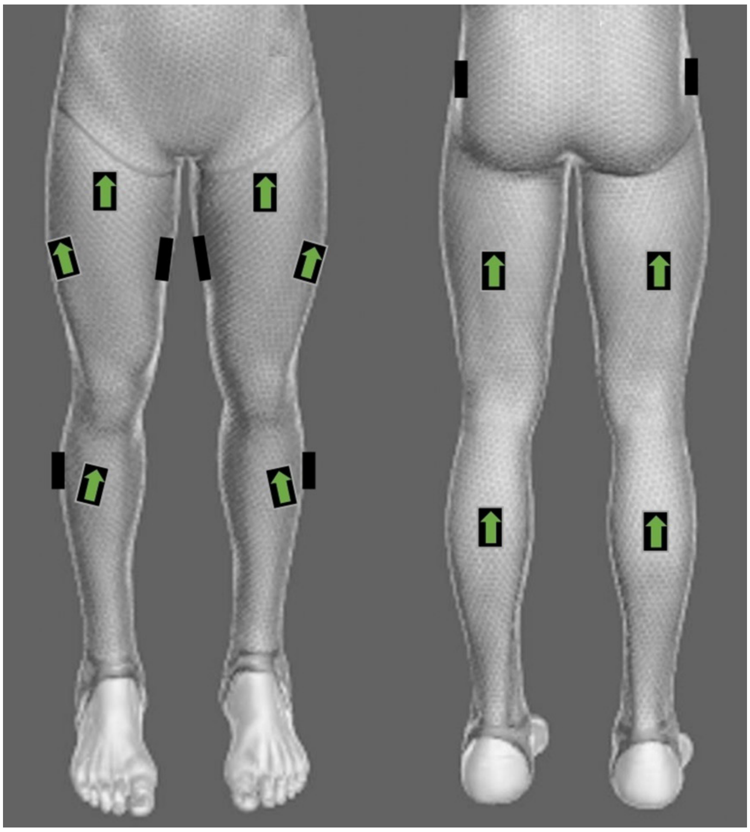

Figure 1. Locations of surface EMG attachment.

Data analysis

For kinematic analysis, the behavioural events for the roundhouse kick were defined as follows: start, heel off, toe-off, maximal knee flex (MKF), and impact. The start event was the time at which a visual cue was shown. The heel-off and toe-off events were determined when the heel and toe marker detached from the ground, respectively. The impact event was determined when the toe marker on the dominant leg was in contact with the target.

In the study, the roundhouse kick was categorized into the following phases based on the detected event (Figure 2): heel-off phase (start until heel-off), toe-off phase (heel-off until toe-off), knee flexion phase (toe off until MKF), and impact phase (MKF until impact). The time length of the kinematic data was normalized to 100 frames using a spline function [18], such that the data were represented in terms of the percentage (%) of a task. The execution time was determined as the time from the start to impact events.

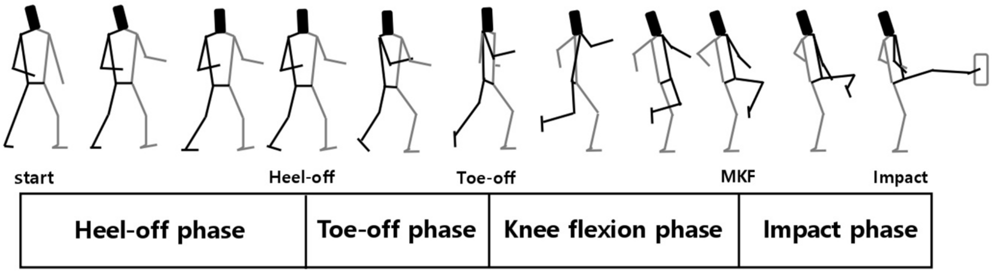

Figure 2. Analysis of each phase based on event phase of roundhouse kick. MKF = maximal knee flexion.

For muscle synergy analysis, EMG signals were processed adequately. To remove noise signals and offset, we used a high-pass filter (third-order Butterworth) at 35 Hz and subtracted each mean value. Subsequently, the EMG data were rectified and a low-pass filter was applied with a 10 Hz cut-off for smoothing. For a comparison of the EMG data among the participants, we normalized the EMG amplitude and time length as follows: the EMG amplitude was normalized from 0 to 1 by the maximal value of each data set in each trial. Furthermore, the time length of the EMG data was normalized to 100 frames (Figure 3), same as that of the kinematic data.

NMF was used in the analysis of muscle synergy for each trial [19] and was computed as follows [20]:

$$\mathrm{EMG0} = \sum_{i=1}^{n} Wi \cdot Ci + e$$

$$\mathrm{EMGr} = \sum_{i=1}^{n} Wi \cdot Ci$$

where,

EMG0 (time × muscle) represents the original EMG data used in the analysis;

EMGr is the reconstructed data after the NMF;

n is the number of synergies ranging from 1 to 16, because 16 activations of muscles were measured;

W is the synergy structure (muscle × n) representing the weighting value of individual muscles in each synergy;

C is the time-dependent synergy activation profile;

e is the residual error.

To determine the number of muscle synergies, we calculated the variance account for (VAF) as follows [20]:

$$\mathrm{VAF} = 1 - (\mathrm{EMG0}-\mathrm{EMGr})^2 / \mathrm{EMG0}^2$$

Similar to previous studies [18, 21], the VAF threshold was set at 90%, indicating that an error as high as 10% was allowed between EMG0 and EMGr.

Clustering analysis

To define similar muscle synergies from all participants, we conducted a clustering analysis. In this study, we used iterative k-means clustering with discriminant analysis [22]. The size of the data matrix for clustering was 16 muscle × ∑nW, where ∑nW is the total number of synergies from all participations in the study (all participations × target types × trials × number of muscle synergies in each trial). To perform k-means clustering, the number of clusters (k) was initially set as the maximum number of muscle synergies during a trial. Subsequently, we performed a discriminant analysis, which involves a supervised learning algorithm, to improve the clustering results. In the discriminant analysis, a linear discriminant analysis was performed when the p-value was greater than 0.05 in Box's M-test. Otherwise, a quadratic discriminant analysis was performed. After clustering, we analysed whether the muscle synergies

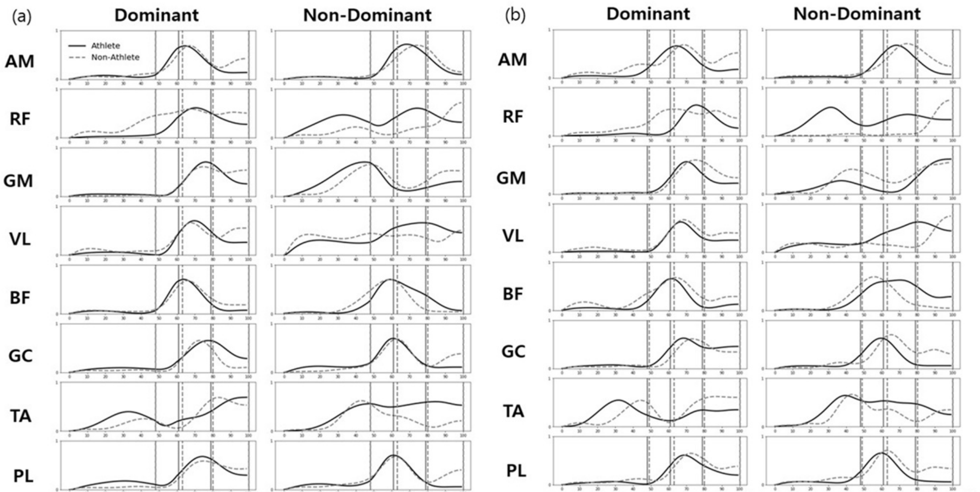

Figure 3. Representative EMG signal of athlete and non-athlete groups for targets of the waist (a) and head (b). Representative EMG signals of adductor magnus (AM), rectus femoris (RF), gluteus medius (GM), vastus lateralis (VL), biceps femoris (BF), gastrocnemius (GC), tibialis anterior (TA), and peroneus longus (PL) are presented.

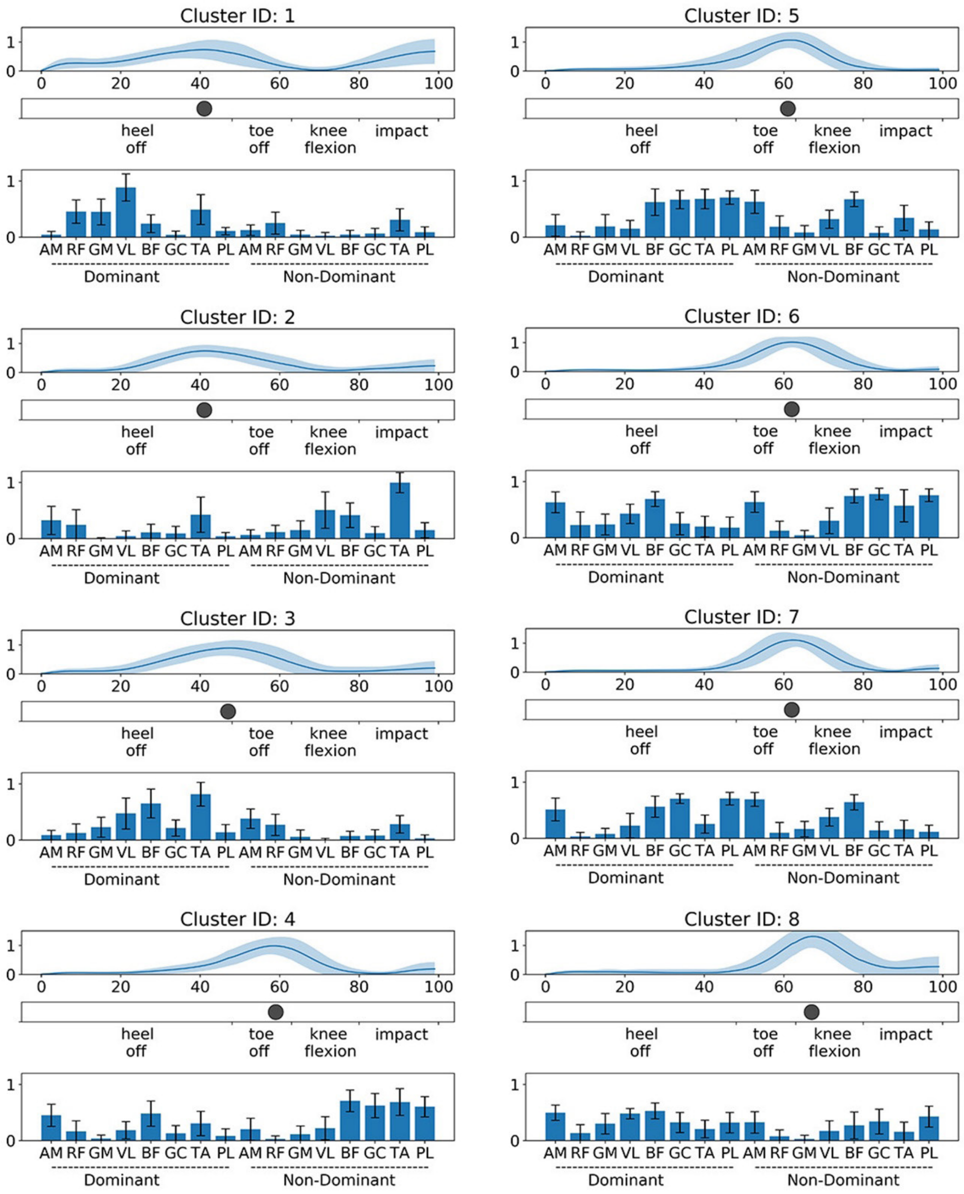

Figure 4. Assignment muscle synergy in clusters 1–8; adductor magnus (AM), rectus femoris (RF), gluteus medius (GM), vastus lateralis (VL), biceps femoris (BF), gastrocnemius (GC), tibialis anterior (TA), and peroneus longus (PL).

extracted from the same trial were assigned to the same cluster because those synergies violated the prerequisite condition stipulating that each muscle synergy should exhibit inherent muscle coordination patterns for performing a task. When the violation condition was detected, the iterative k-means clustering with discriminant analysis was repeated as mentioned above, with a sequential increase in k. Next, the intraclass correlation coefficient (ICC) was analysed to evaluate the similarity of synergies assigned into the same cluster. In this study, the processes above were repeated 1,000 times, and the case indicating the most frequent k-value and the highest mean ICC value was selected. For the selected clustering result, we calculated the proportions of athlete and non-athlete groups within each cluster.

Statistical analysis

An independent t-test was conducted to compare the execution time of the roundhouse kick between athletes and non-athletes. All statistical analyses were performed using IBM SPSS/pc+ Windows (version 26.0). The level of significance was set to 0.05.

RESULTS

Execution time of roundhouse kick

The execution times of the roundhouse kick in the athletes and non-athletes were 0.84 ±0.12 s, 1.06 ±0.17s (*F* = 2.060, *p*<0.001), respectively.

Number of muscle synergies

The number of muscle synergies ranged from two to four for a roundhouse kick. The athletes indicated 2.95 ±0.15 and 3.10 ±0.20 synergies at the weight target height and head target height, respectively, whereas the non-athletes indicated 2.94 ±0.27 and 2.98 ±0.30 synergies, respectively.

Clustering

Within each cluster (a clustering analysis was performed, in which 16 clusters indicating 16 types

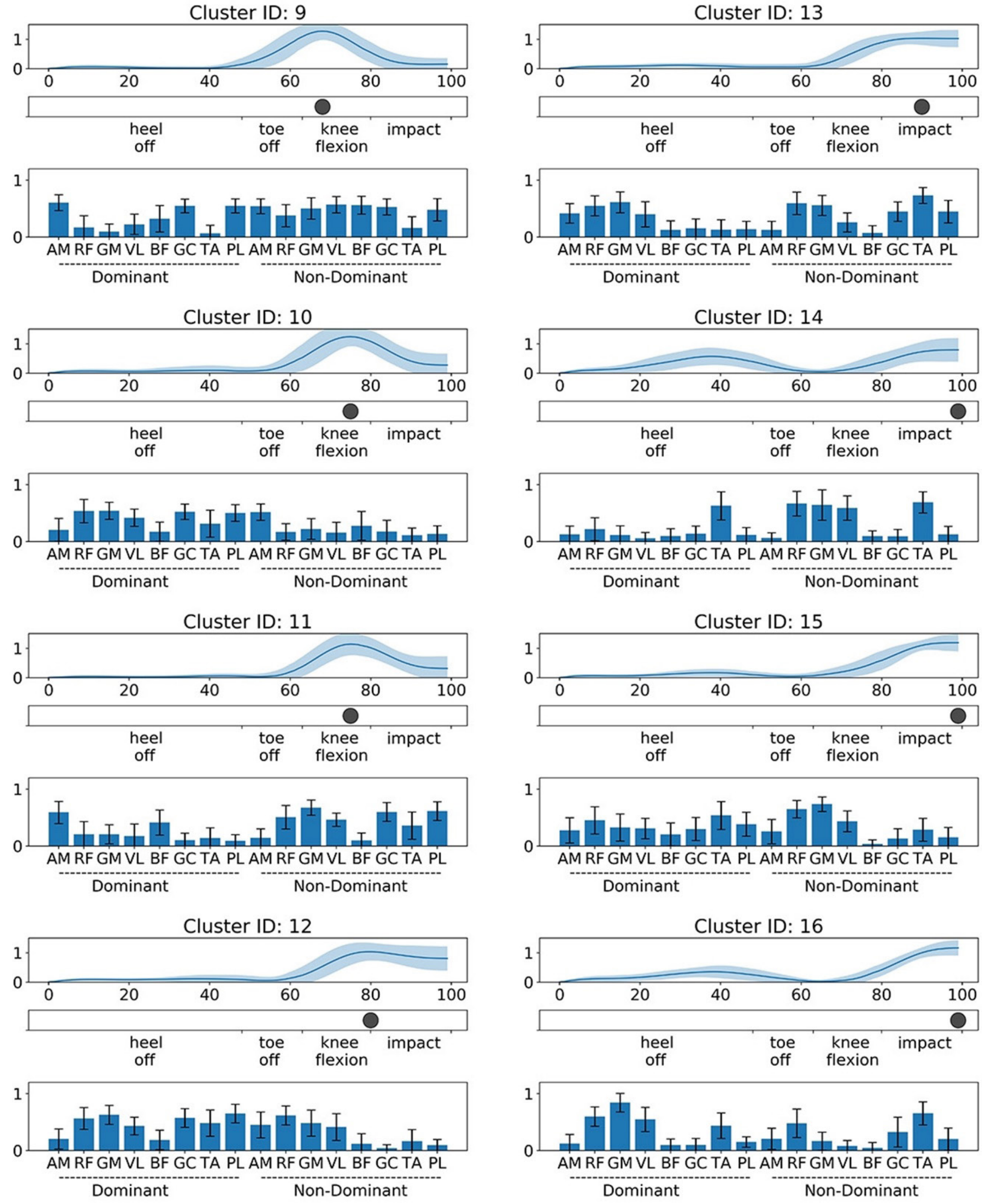

Figure 5. Assignment muscle synergy in clusters 9–10; adductor magnus (AM), rectus femoris (RF), gluteus medius (GM), vastus lateralis (VL), biceps femoris (BF), gastrocnemius (GC), tibialis anterior (TA), and peroneus longus (PL).

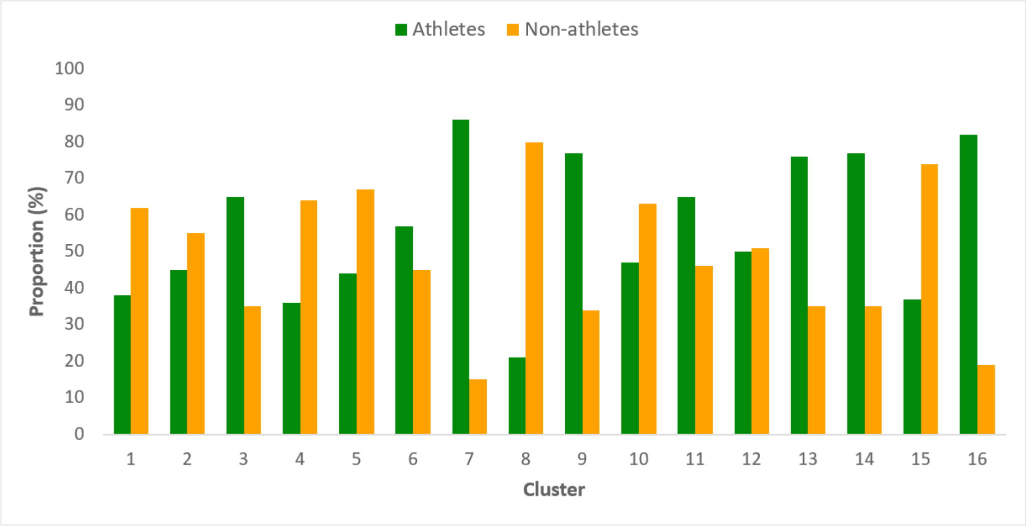

Figure 6. Relative proportions of athletes and non-athletes.

of muscle synergies used for the roundhouse kick were presented), the similarity of the muscle synergies was presented with the ICC values, and the mean and standard deviation across all clusters were 0.61 ±0.9. Figures 4 and 5 show the synergy activation and structure in each cluster. Figure 6 shows the relative proportions (%) of the athletes and non-athletes within individual clusters. Based on Figure 6, we defined two athlete-preferred clusters (clusters 7 and 16) and two non-athlete-preferred clusters (clusters 8 and 15). In addition, participants who used athlete-preferred clusters 7 and 16 more indicated shorter execution times than other participants using non-athlete-preferred clusters 8 and 15 (Figure 7).

Characteristics of each phase

In the heel-off phase, clusters 1 to 3 were used. Clusters 1 and 2 showed a simple structure by the main co-activation of the dominant VL and non-dominant TA, respectively. Cluster 3 comprised the dominant thigh muscles and TA.

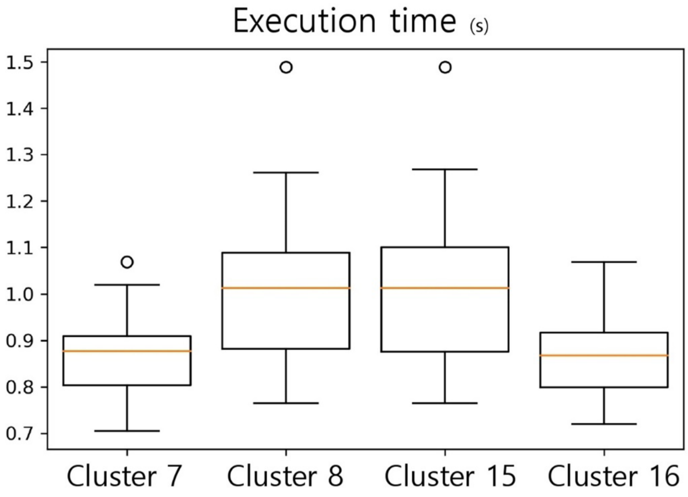

Figure 7. Execution time differences in clusters 7, 8, 15, and 16. Execution times are shown with box plots for each athlete- and non-athlete-preferred cluster. Clusters 7 and 16 are athlete-preferred ones, whereas cluster 8 and 15 are non-athlete-preferred ones. Error bars indicate 95% confidence interval, and boxes indicate 25th–75th percentiles with a median.

In the toe-off phase, clusters 4 to 7 were observed. Cluster 4 mainly comprised non-dominant shank muscles and BF. The main muscles of cluster 5 was the dominant BF and GC as well as the non-dominant thigh muscles. Similar to cluster 4, cluster 6 was constructed with non-dominant shank muscles, AM, and BF, as well as the dominant AM and BF. Cluster 7, which was preferred more by the athletes, exhibited a similar structure as clusters 4 and 6 in the dominant muscle co-activation; however, the dominant plantar flexors were co-activated, whereas the non-dominant shank muscles were not.

In the knee flexion phase, muscle synergies were assigned to clusters 8 to 12. Cluster 8 was a synergy that was preferred more by the non-athletes, and it mainly comprised the dominant thigh and shank muscles as well as non-dominant shank muscles. Cluster 9 was similar to cluster 7 but indicated an increased co-activation of the non-dominant thigh muscles, GM, and PL. Cluster 10 comprised the dominant thigh muscles, shank muscles, and GM as well as the non-dominant AM. Cluster 11 showed the co-activation of the AM and BF in the dominant leg as well as all muscles in the non-dominant leg except for the AM and BF. Cluster 12 was similar to cluster 10 and presented an additional co-activation of the non-dominant AM, GM, and VL.

In the impact phase, we observed muscle synergy patterns assigned to clusters 13 to 16. Cluster 13 showed an increased co-activation of the dominant thigh muscles and the non-dominant RF, GM, and shank muscles. The main muscles of cluster 14 were the dominant TA and non-dominant thigh muscles, GM, and TA. Cluster 15, which was preferred more by the non-athletes, showed the co-activation of the non-dominant RF and GM. Cluster 16, which was preferred more by the athletes, comprised the dominant thigh muscles and GM as well as the non-dominant TA.

DISCUSSION

In the roundhouse kick, we identified two to four muscle coordination patterns in each trial and discovered that our participants exhibited 16 pattern types. Furthermore, our results demonstrated the existence of athlete- and non-athlete-preferred muscle coordination patterns, separately, in the roundhouse kick.

In the study, clusters 7 and 16 were preferred more by the athletes. Cluster 7 showed that the dominant AM, BF, GC, and PL as well as the non-dominant AM and BF were co-activated in the toe-off phase. Cluster 7 was similar to clusters 4 and 6, but it indicated an additional co-activation of the dominant GC and PL with a reduced co-activation of non-dominant shank muscles. We assumed that cluster 7 was associated with creating a ground reaction force with high speed in taekwondo competitions. Specifically, the co-activation of the dominant GC and PL muscles may be performed to raise the dominant leg by creating a high ground reaction force in the toe-off phase. The high ground reaction force generated from the dominant leg can facilitate the quick motion of the roundhouse kick. Previous analyses of the roundhouse kick indicated that the ground reaction force in all axes was significantly higher in elite athletes [12], and that the latter exhibited an increased activation of the GC at the lift-off phase [23]. Moreover, the elite athletes demonstrated greater ground reaction forces in the bandal kick [11]. Furthermore, the co-activation of the BF and AM of the non-dominant leg may provide momentum for the body to move forward with hip extension.

Among three clusters in the impact phase, cluster 16 described the patterns that were preferred more by the athletes, i.e., those of the dominant RF, GM, and VL as well as the non-dominant TA. Previous studies indicated that the dominant VL, RF, and GM were activated in the impact phase [11, 17]. We presumed that cluster 16, which involves the co-activation of the dominant knee extensor and hip abductor, might be associated with high speed in taekwondo competitions. In this study, the execution time indicated a significant difference, and participants who used cluster 16 required shorter execution times than those who used clusters that were more preferred by non-athletes. Furthermore, previous studies indicated that the execution time differed significantly by proficiency level [11, 24]. Therefore, we assumed that the co-activation of the RF, GM, and VL contributed to the difference in kick speed between athletes and non-athletes. These results imply that the athletes would use the muscle coordination patterns of clusters 7 and 16 for performing the roundhouse kick.

In this study, we discovered that the muscle coordination patterns of clusters 8 and 15 were preferred more by the non-athletes. Cluster 8 indicated the co-activation of the dominant AM, VL, and BF as well as the non-dominant PL in the knee flexion phase. The co-activation in cluster 8 was focused on the dominant leg, whereas the clusters preferred by the athletes, i.e., clusters 9 and 11, showed the co-activation of the non-dominant GM and PL in the knee flexion phase. For an individual muscle function, the co-activation of the non-dominant GM and PL might be associated with joint stability for body-weight support. Cluster 15 comprised the dominant TA and non-dominant RF, GM, and VL in the impact phase. Compared with cluster 16 preferred by the athletes, cluster 15 showed a relatively extensive co-activation of non-dominant muscles. Our results demonstrate that the muscle coordination patterns differed between athletes and non-athletes, indicating different movement strategies based on the task proficiency.

The current study had several limitations. First, we observed only lower-body muscles. Because the roundhouse kick included trunk movement, future studies should include measurements based on different muscles. In this study, we measured the execution time as an indicator of the kicking performance. Because kicking power is also an important factor, a further study for identifying the relationship between kicking force and muscle coordination patterns might be useful to understand motor control mechanism in the roundhouse kick.

CONCLUSIONS

This study was designed to identify specific muscle coordination patterns for the roundhouse kick motion in athletes and non-athletes. As the results, the execution times of the roundhouse kick in the athletes was significantly faster and those of non-athletes. The clustering analysis exhibited that in the toe-off and impact phases, the athletes focused on the co-activation of the dominant leg to quickly perform the roundhouse kick. By contrast, the non-athletes emphasized the co-activations of the leg muscles in the impact and knee flexion phases. Our results, which define athlete-specific muscle coordination patterns, can be utilized for establishing a training strategy of the roundhouse kick.

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