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不同肌肉组选择导出模块对组间肌电反复性的影响

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摘要：目的　评价组间肌电反复性对不同肌肉组选择导出模块的影响。**方法**　记录 12 名参与实验者在自选速度下行走时 16 块肌肉的肌电图。用组内相关系数评价每个步行周期的肌肉兴奋度和肌肉模块。依据肌肉兴奋度的反复性，区分出 3 种类型的肌肉组。**结果**　可靠肌肉组显示出较高的组内相关系数（>0.4），而全身肌肉组和混合肌肉组显示出较低的组内相关系数（<0.4）。3 种类型肌肉组比较，可靠肌肉组分析得出的模块具有最好的反复性，全身肌肉组和混合肌肉组的反复性较低。**结论**　具有较高可靠性的肌肉兴奋性能够得出较一致的模块。得出一致模块的方法非常重要，尤其是在依靠肌肉兴奋性反馈而改变的运动模式中。

关键词：肌肉兴奋度；肌电图；行走；稳定性；重复性
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Choice of Muscles for Extracting Consistent Motor Modules: The Effect of Trial-to-Trial Electromyography Repeatability

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Abstract：**Objective**　To identify the effect of the repeatability of muscle activations on extraction of consistent motor modules across trials. **Methods**　The activities of sixteen muscles in twelve subjects who consistently walked at a self-selected speed were recorded. The intraclass correlation coefficient (ICC) was used to identify inter-stride repeatability of muscle activities and motor modules. Based on the repeatability of muscle activation, three types of muscle sets were organized. **Results**　The reliable set containing the muscles showed high ICC（>0. 4）, but the whole-body and mixed sets containing the muscles showed poor ICC（<0. 4）. When motor modules were extracted from each set, the reliable set showed the highest repeatability of motor module extraction, but the whole-body and mixed sets presented significantly lower repeatability. **Conclusions**　Greater repeatability of muscle activations result ed in consistent motor modules. Extraction of consistent motor modules was a critical issue, especially in real-time motion recognition based on muscle patterns.

Key words：muscle activation；electromyography(EMG)；walking；stability；repeatability

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Multi-joint movement involves the co-activation of muscle groups and generates complex electromyography (EMG) patterns. In previous studies, the analysis of motor modules or muscle synergy has been considered as a valuable tool for visualizing co-activation of individual muscles in human behavior[1-3]. This analysis has shown the activation of a group of muscles as individual units that are flexibly coordinated to achieve purposeful motor behaviors[1,4].

In the case of a human walking, the literature has adequately described that this motor behavior consists of three to six modules[3,5-10], but the inter-stride repeatability (ISR) of motor modules is not often considered[11-14]. Greater repeatability of motor module extraction is encouraged when motor modules are used to classify human behaviors in real-time myoelectric control. The central nervous system produces consistent motor patterns to achieve task purpose in repetitive behaviors[11]. Hence, it has been considered that a motor module should exhibit high repeatability between gait cycles[3]. To support this notion, previous studies have demonstrated the repeatability of motor modules between gait cycles[12-14]. However, studies have rarely considered the method for choosing a muscle set for extraction of consistent motor modules among repetitions of the same functional movement.

Thus, this study aimed to provide practical guidance for choosing muscles to extract consistent motor modules in human natural walking. It was hypothesized that a set of muscles containing neck and abdominal muscles with poor ISR would decrease the repeatability of motor modules because previous studies presented that the activation of neck and abdominal muscles was not consistent across strides[15-19]. Since motor modules indicate specific patterns of muscle activity of motor behavior, the intraclass correlation coefficient (ICC) is used to identify the repeatability of muscle activity and motor modules across strides in this study. The repeatability of motor modules between different muscle sets based on ICC values was compared as well.

1 Methods

1.1 Participants

Twelve young adults, 5 females and 7 males, age (24.3 ± 1.8), body mass (64.7 ± 12.0) kg; height (169.0 ± 10.4) cm, right-handed dominant side, were recruited into the study after providing informed consent. The preferredkicking limb was determined as dominant leg. Participants were excluded if they had orthopedic surgery, a musculoskeletal injury within the previous six months, chronic arthritic disease, neurological disorders, or severe cardiovascular disease. Ethical approval was obtained from the Institutional Review Board.

1.2 Procedure

EMG signals were recorded at 1 kHz using a wireless EMG system TeleMyo 2400R (Noraxon, Scottsdale, AZ, USA). The 16 muscles on the right side were recorded as follows:sternocleidomastoid (SCM), tibialis anterior (TA), peroneus longus (PL), rectus femoris (RF), vastus medialis (VM), adductor (ADD), external oblique (EO), gluteus medius (G_{med}), tensor fasciae latae (TFL), erector spinae cervical region (ESC), erector spinae thoracic region (EST), erector spinae lumbar region (ESL), gluteus maximus (G_{max}), biceps femoris (BF), medial gastrocnemius (MG), and soleus (SOL) [20]. Electrodes were attached over the belly of individual muscles and inter-electrode distance was 2 cm. Before electrode placement, the skin was abraded and cleaned with alcohol to minimize impedance.

Kinematic data were collected in order to correctly define each gait cycle at a sampling frequency of 100 Hz using six motion-capture cameras (Hawk Digital Camera, Motion Analysis Santa Rosa, CA, USA). The marker set was based on the Helen Hayes marker set which includes head-arms-trunk (HAT), thigh, shank, and foot segments[21]. The gait cycle was defined as the interval between two consecutive right heel strikes.

Participants walked 8 m at a self-selected speed (1.2-1.5 m/s) in each trial[22-23] because the unrestrained gait speed will reflect their daily walking manner [24]. Before test trials, participants performed 10 times of practice trials to establish their self-selected walking speed. After familiarization, EMG and kinematic data for individual gait cycles were recorded for six trials.

1.3 Data processing

Six gait cycles were selected for subsequent analysis. Each raw EMG signal was high-pass filtered (2nd order, 30 Hz), demeaned, full-wave rectified, and low-pass filtered (2nd order, 5 Hz)[14]. Next, each EMG envelope was scaled by gait cycle using synchronized kinematic data. Each gait cycle was resampled to contain 100 points (1%-100% from right heel strike to right heel strike) using cubic spline interpolation.

1.4 Motor module analysis

Motor modules were computed using non-negative matrix factorization (NMF) as described previously[25]. The process of NMF was applied to each of the EMG matrices. Prior to NMF, each EMG was normalized by its peak value during walking, so that EMG data were within the range of 0 to 1 in amplitude. The motor modules from individual gait cycles were extracted to minimize loss of original EMG patterns during module extraction [12] and to maintain motor variability[26]. The motor module was obtained according to the following formula:

$$\mathrm{EMG_o} = \sum_{i=1}^{n} \mathrm{W_i C_i} + \mathrm{e}, \quad \mathrm{EMG_r} = \sum_{i=1}^{n} \mathrm{W_i C_i}$$

where n is the number of modules (range: 1 to 16), i is an identification number for each module, W is a module structure matrix (muscle × n) indicating the weighting vectors of individual muscles for each module, C is a module activation matrix ($n \times$ time) indicating time-varying activation profiles, and e is residual error. $\mathrm{EMG_r}$ is a reconstructed EMG matrix (muscle × time) resulting from the multiplication of W and C. In the process of NMF, the parameters used were as follows: 2×10^3 replicates, 1×10^4 maximum iterations, 1×10^{-4} minimum threshold for convergence, and 1×10^{-4} threshold for completion.

In alignment with previously published studies indicating high similarity between $\mathrm{EMG_o}$ and $\mathrm{EMG_r}$ for validity of the NMF decomposition[7,27], the variability accounted for (VAF) was used to identify the number of muscle synergies. VAF for total muscles was computed as follows:

$$\mathrm{VAF}(\%) = (1 - (\mathrm{EMG_o} - \mathrm{EMG_r})^2 / \mathrm{EMG_o^2}) \times 100$$

In this study, the VAF cutoff was 90% of total VAF so that the number of modules was defined as the lowest number that resulted in over 90% of total VAF[14].

To arrange similar modules across the six sets at each module, we categorized data using k-means clustering to identify groups of modules that were similar across the individual gait cycles. The k-means clustering is a commonly used clustering method to group similar data point into k clusters in a multi-dimensional space. The clustering was performed using the module structure matrices (W) as parameters so that data were analyzed in a 16 dimensional space. The value of k was set at the number of modules (n = 3-5). Maximal iteration was 10 000 and replicates were 100.

Based on the $\mathrm{ICC_{2,1}}$, the ISR of muscle activities and motor modules was presented, respectively. First, the ICC of each muscle was tested for the six trials. In this study, an ICC greater than 0.81 was considered excellent, 0.61-0.80 was good, and 0.40-0.60 was fair ISR[28]. Then, three types of muscle sets was defined, i.e., the whole-body set, the reliable set, and the mixed set. The whole-body set consisted of all muscles that were measured in the study. If the ICC of one muscle was higher than 0.4, indicating fair ISR, this muscle was classified into the reliable set. The mixed set was the control condition comparable to the reliable set. It was defined as the muscle set containing unreliable muscles with an ICC less than 0.4. Since the number and region of muscles influence module structures and activations, those were matched between the reliable and mixed sets. After extraction of motor modules from each set, the ICCs of module structures and activations across the six trials were also examined. Then, the ISR values of motor modules in each muscle set were represented by mean and minimum ICC values.

1.5 Statistical analysis

Two-way repeated measures analysis of variance (RMANOVA) was used to identify significant differences in VAF values between muscle set and the number of modules. The Friedman test or RMANOVA was used to compare the number of modules and mean and minimum ICC values of module structures and activations among three types of muscle sets. The mean ICC values, except for the module with the minimum ICC value, were also examined to identify whether inconsistent muscle activation affected the overall repeatability of module extraction. Post-hoc testing was conducted with nonparametric pairwise comparisons or Scheffe's method. The significance level was set at $P<0.05$. Statistical analysis was performed using SPSS 19 (IBM Corp., Somers, NY, USA).

2 Results

In the ISR for 16 individual muscles, EST, ESL, and leg muscles showed good to excellent repeatability (mean ICC range: 0.58-0.86), but SCM, ESC, and EO showed poor ISR (mean ICC range: 0.09-0.21) as shown in Table 1. Based on ICC values of individual muscles, the reliable set was rearranged to include EST, ESL, and leg muscles ($n=13$), and the mixed muscle set to include SCM, ESC, EO, and leg muscles ($n=14$). The patterns of EMG data from a representative subject were shown in Fig.1.

Tab.1 Intra-class correlation coefficients for each muscle

Muscle	Mean	Standard deviation	Muscle	Mean	Standard deviation
SOL	0.862	0.067	PL	0.620	0.187
MG	0.861	0.069	RF	0.614	0.219
ESL	0.744	0.116	G_{max}	0.600	0.174
VM	0.735	0.116	ADD	0.581	0.145
TA	0.710	0.133	TFL	0.558	0.197
G_{med}	0.686	0.160	EO	0.209	0.203
EST	0.656	0.158	ESC	0.153	0.145
BF	0.656	0.163	SCM	0.093	0.125

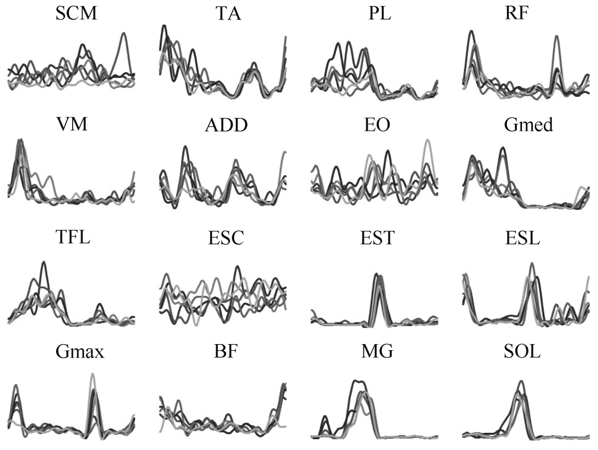


Fig.1 Representative EMG of 16 muscles in six walking trials

The number of modules based on 90% of VAF cutoff was four or five in all muscle sets (Fig.2). Two-way RMANOVA demonstrated significant interaction between muscle sets and the number of modules ($F_{4,44}=3.759$, $P=0.031$). In post-hoc testing, there were significant differences in VAF values between the whole-body and reliable sets, but no differences between the reliable and mixed sets. The Friedman test and the nonparametric pairwise comparisons indicated that the whole-body set showed a higher module number than the reliable set ($P<0.01$). Median value (interquartile range) of the whole-body, reliable, and mixed sets were 5 (0), 4 (0), and 4 (1), respectively.

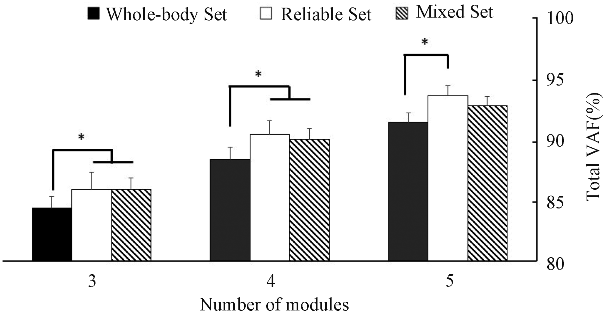
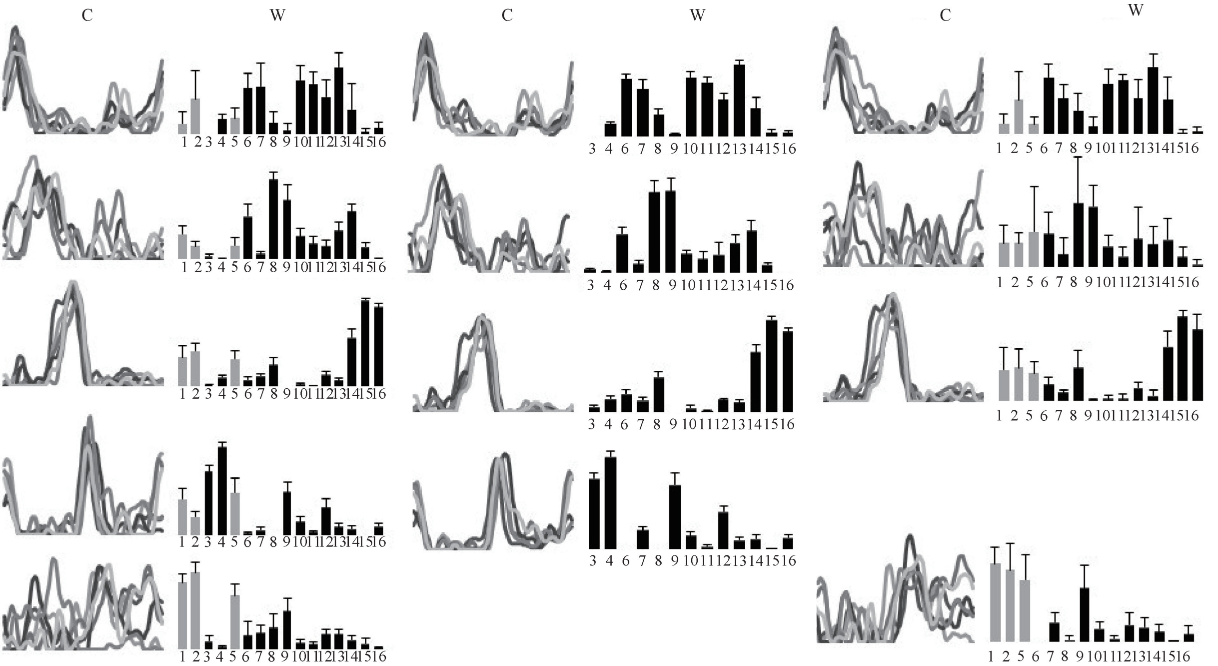


Fig.2 Average of total variance accounted for (VAF) in three muscle sets

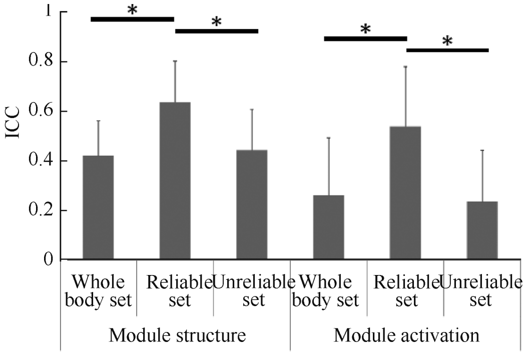
Module structures and activations across the six trials were arranged by clustering and then the ICC values were quantified. The repeatability of module structure and activation was represented with minimum and mean ICC values. The repeated measures ANOVA and Scheffe's test indicated that the mean ICC of the reliable set showed good repeatability that was significantly higher than that for other sets ($P<0.05$). This tendency was identified in both module structures and activations regardless of mean [Fig. 3(a)] and minimum ICC value [Fig. 3(b)]. No differences in ICC values were observed between the whole-body set and the mixed set. Mean ICC values, except for the module with the minimum ICC value, were also significantly higher in the reliable set than the whole-body or the mixed set (module structure: $F_{2,22}=31.540$, $P<0.001$, module activation: $F_{2,22}=15.546$, $P<0.001$).

In Fig. 4, Module activations (C) and structures (W) were displayed using line and bar graphs, respectively. The bar graphs were presented with mean and standard deviation (SD) values. Gray bars indicated the muscles showing low repeatability between trials. We noted that similar modules between the muscle sets were presented in the same row but the pattern of module activations and SD values of module structures notably varied in the whole-body and mixed sets.

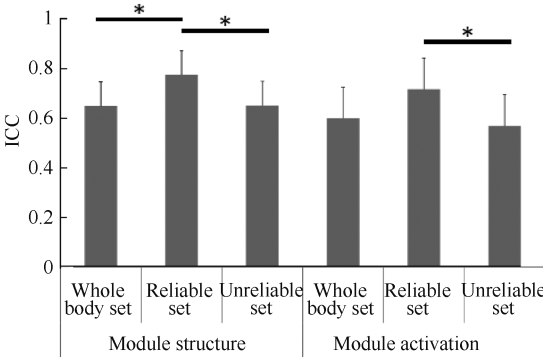


(a) Whole-body set (b) Reliable set (c) Unreliable set

Fig.4 Examples of motor modules across whole-body, reliable, and unreliable muscle sets for six walking trials C, W represented module activations and structure; 1-16 represented SCM, ESC, EST, ESL, EO, Gmed, Gmax, TFL, ADD, RF, VM, BF, TA, PL, MG, and SOL



(a) Minimum ICC values



(b) Mean ICC values

Fig.3　Intra-class correlation coefficient (ICC) values of three types of muscle sets

3　Discussion

The main purpose of the current study was to provide guidance for muscle choice for motor module analysis. Unfortunately, a muscle set for motor module analysis has been determined by the subjective judgment of researches. Furthermore, there was no practical guidance to choose a muscle set for extraction of consistent motor modules in biomechanical experiments. Our findings suggested that repeatability of muscle activities were important to extract consistent motor module in repetitive motor tasks.

As a single motor command recruits pools of α-motor neurons and simultaneously activates multiple muscles[2,29], motor module analysis has been used to exhibit neuromuscular co-activation patterns in the process of achieving purposeful behavior. Given that the motor command for the performance recurs with low variance in repetitive trials[11], it is hypothesized that if motor modules reflect the motor command, they should be consistent in repetitive gait cycles. Our findings showed that consistent motor modules were extracted from a muscle set with a high ISR. That is, if the activity of a certain muscle showed high consistency in repetitive gait cycles, this muscle could be considered as a critical element for motor module analysis.

The lower ICC of the motor modules in the whole-body and mixed sets suggested that motor moduleanalysis was affected by the ISR of EMG signals. As shown in Fig.4, muscles such as SCM, ESC, and EO, which had low ICC values, mainly contributed to the last modules of the whole-body and mixed sets. A module with low repeatability was also observed in a previous study when neck and abdominal muscle activities were included in module extraction[6]. These irregular patterns might indicate reactive compensation through feedback control for stabilizing the head and trunk regions. However, when comparing the reliable set and the other sets, inclusion of the neck and abdominal muscles in motor module analysis affected the repeatability of other module activations and structures. It is recommended that the repeatability of the whole motor modules, including muscles with high repeatability, be considered when extracting consistent motor modules in rhythmic and repetitive behavior.

High repeatability of motor modules was required when NMF was used for classifying motor behaviors in real-time myoelectric control. Previous studies suggested that EMG signals could indicate decision-making of human motor behavior and application of this information for robot controls[30]. This real-time control scheme based on EMG has been developed using machine learning classifiers such as NMF[31-32]. It was expected that the repeatability of EMG signals and motor modules would be critical for the selection of muscles in real-time myoelectric control.

Motor module analysis without verifying repeatability of individual muscles can threaten to decrease measurement validity. Motor module analysis has been extracted from the averaged EMG for repetitive task trials[5-10]; therefore, if several muscles having low ISR were included in the original EMG matrix, variable activation patterns of these muscles could be omitted in the averaging process. Furthermore, the averaged EMG of the muscles having low repeatability would not represent EMG signals for the task. That is, the use of the averaged EMG lacking repeatability could decrease measurement validity. Instead of EMG averaging, a previous study suggested concatenation of EMG signals as a preparatory step for module extraction[12], but this method decreased the quality of EMG reconstruction, indicating greater omission of original EMG characteristics after module extraction as compared to that in EMG for a single gait cycle. Verifying EMG repeatability would be also useful to evaluate the contamination with noise signals during repetitive behaviors. In the case of low-activated muscles during walking, such as EO, SCM, and ESC[19,33-34], it was more difficult to discriminate true EMG amplitude from noise than from other phasic muscles showing specific characteristics. Furthermore, since each EMG signal was normalized by its maximum value before NMF, meaningless signal amplitudes could be overstated, even when the muscles did not significantly participate in motor behavior. The repeatability of motor modules was influenced by the consistency of module structures and activation across trials. Hence, even though EMG data were scaled by other normalization methods, inconsistent EMG signals across trials could still decrease the repeatability of motor modules. In a previous study, when EMG signals during walking were normalized by unit variance, abdominal muscles caused a motor module that features were not consistently recruited throughout gait cycles[6].

The whole-body set was recommended for identifying the number of motor modules indicating muscle coordination complexity[35]. In previous studies, whole-body EMG signals had been used in module extraction to understand the number of modules in walking[5-6,8-9]. In this study, module extraction using the reliable and mixed sets did not exhibit five modules as shown in the whole-body set. Instead, module structures and activations in the whole-body set were generally preserved if key muscles in the corresponding module were selected in the reliable and mixed sets, although the number of muscles in each set was different[5]. These results suggest that if motor module analysis aims to describe muscle coordination complexity, EMG signals should be recorded as many as possible from whole-body region. In this study, motor modules were extracted at a self-selected speed only. To generalize our findings, further studies that use analytical approaches similar to ours should be performed with different motor behaviors.

The results showed that the subjects tended to reproduce activation patterns of lower back and leg muscles rather than neck and abdominal muscles in repetitive gait cycles. In human walking, the ISR of EMG signals in leg muscles has been reported and the level of repeatability was good to excellent[36-39]. Although one study reported low ISR of PL muscle [38], our study supported good repeatability of this muscle during walking. A definitive study for ISR of neck and trunk muscles in over-ground walking was not found. In this study, the ICC values for individual muscles suggested that EO, SCM, and ESC muscles had low repeatability in walking. At a self-selected speed, the EO muscle was used at a low activation level of less than 5% of maximal voluntary contraction in the gait cycle[33-34]. However, it was demonstrated that the activation pattern of the EO muscle corresponded to increasing gait speed[6,18]. In addition, the activation period of EO was definitely different between walking and running[17]. These results indicated that EO was mainly activated in walking at high speed or running, but not at a self-selected speed. In case of neck muscle activity in walking, a previous study showed irregular and low amplitude EMG of SCM and ESC muscles[19].

4　Conclusions

The activation patterns in back and leg muscles were highly reproducible in human natural walking at self-selected speed. However, the neck and abdominal muscle activities showed low repeatability. ISR analysis of three types of muscle sets showed that inclusion of muscles showing low repeatability affects the total repeatability of the module structures and activations. High repeatability of EMG signals should be utilized as a criterion to select a muscle set for motor module extraction in real-time myoelectric control. In contrast, if the study aims to identify muscle coordination complexity, motor modules should be extracted from the whole-body muscle set.

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