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Impact of different bilateral knee extension strengths on lower extremity performance

Kilchoon Cho, MS*, Makoto Suzuki, PhD, Naoki Iso, PhD, Takuhiro Okabe, PhD, Hiroshi Goto, PhD,
Keisuke Hirata, PhD, Junichi Shimizu, PhD

Abstract

Despite the impact of leg muscle strength on lower extremity motor performance—including walking and sit-to-stand transfer—it remains difficult to predict the relationship between bilateral leg muscle strength and lower extremity performance. Therefore, this study was designed to predict lower extremity function through the differential modeling of logarithmic and linear regression, based on knee extension strength.

The study included 121 individuals living in the same community. The bilateral strengths of the knee extensors were measured using a handheld dynamometer, and the Timed Up & Go test (TUG) performance time and 5-m minimum walking times were assessed to predict lower extremity motor functions. Bilateral normalized knee extension muscle strengths and lower extremity motor function scores, including walking or TUG performance times, were assessed on the logarithmic and linear models. The Akaike information criterion (AIC) was used to evaluate the coefficient compatibility between the logarithmic regression model and the linear regression model.

The AIC value for the linear model was lower than that for the logarithmic model regarding the walking time. For walking time estimation in the linear model, the coefficient value of knee extension strength was larger on the strong than on the weak side; however, the AIC value for the logarithmic model was lower than that for the linear model regarding TUG performance time. In the logarithmic model's TUG performance time estimation, the coefficient value of knee extension strength was larger on the weak than on the strong side.

In conclusion, our study demonstrated different models reflecting the relationship between both legs' strengths and lower extremity performance, including the walking and TUG performance times.

Abbreviations: AIC =Akaike information criterion, SD = standard deviation, TUG = Timed Up & Go.

Keywords: knee extension strength, lower extremity motor performance, rehabilitation, sit-to-stand, walking

1. Introduction

Walking and sit-to-stand progression are considered essential lower extremity motor functions in daily life[1–5]; however, motor performance declines with aging[6–8] and is associated with daily dysfunction,[9–12] falls,[13] cognitive disorder,[14–16] decreasing quality of life,[17] hospitalization,[18,19] and mortality.[20–22] Previous studies have reported that weakness in both legs is an important risk factor for the inability to perform lower limb motor functions, such as sitting-to-standing movement and walking.[1,11,23–26] Therefore, a decline in the muscle mass of both legs is considered a major factor for the development of muscle weakness in older adults and is obvious in regions, such as Japan, the United States, and Europe, where society is dramatically aging.[1,6,26,27] Heterogeneous reductions in both legs' muscle strengths in particular may be clinically relevant to determine the relationship between lower extremity motor performance and leg muscle strength.[7]

The association between strength and performance has been estimated by both linear and non-linear models. Cross-sectional studies[28] on motor performance and strength have traditionally used linear regression modeling; however, a previous study[29] suggested that the association between motor performance and strength may be curvilinear. Exceeding or increasing the intensity of this threshold level cannot improve task performance; below the threshold, a stronger relationship between change in strength and change in performance should be evident. Nevertheless, it remains difficult to predict the relationship between lower extremity motor performance and leg muscle strength. Several aspects should be addressed, such as which side of the leg (i.e., weak or strong) as well as which model based on muscle strength (logarithmic or linear regression) can predict lower extremity motor performance. By predicting lower limb function in community-dwelling people according to knee strength, training to restore lower limb function will be more evidence-based in an

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The datasets generated during and/or analyzed during the current study are not publicly available, but are available from the corresponding author on reasonable request.

Faculty of Health Sciences, Tokyo Kasei University, Saitama, Japan.

* *Correspondence: Kilchoon Cho, 2-15-1 Inariyama, Sayama, Saitama 350-1398, Japan (e-mail: cho-k@tokyo-kasei.ac.jp).*

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aging society. Thus, accurate prediction of lower extremity motor performance would provide crucially important information for both health care administrators and individual patients.

Therefore, this study was designed to assess the relationship between lower extremity motor performance and knee extension strength, and to predict lower extremity motor performance via the differential modeling of logarithmic and linear regression, based on knee extension strength. To the best of our knowledge, this is the first study to demonstrate the balance of leg strength needed to perform functional tasks. Considering the findings of previous studies regarding lower extremity function, we hypothesized the following: there is a suitable balance between both legs' muscle strengths, allowing the prediction of lower extremity motor performance; and lower extremity motor performance may be accurately predicted by linear or logarithmic regression models based on both legs' muscle strengths. Here, we predicted balance of muscle strength in both legs for lower limb motor function by applying linear or logarithmic regression modeling.

2. Methods

The research procedure was approved by the Research Ethics Committee of Tokyo Kasei University and performed in accordance with the principles of the Declaration of Helsinki. All participants were fully informed of the purpose and procedure of the study prior to participation. Written informed consent was obtained from each participant.

2.1. Eligibility criteria

The eligibility criteria included the following: community-dwelling individuals; absence of palsy, knee pain, and injury; and no use of assistive devices for walking and sit-to-stand. The target sample size was based on a desired 90% statistical power to detect changes in lower extremity motor performance and muscle strength, with a 0.90 effect size and a 2-sided α-level of 0.05. Inputting these parameters into the Hulley matrix[30] yielded a sample size of 113; accordingly, we planned to retrospectively recruit 113 patients from a database of survey for Tokyo and Saitama regional area for the analysis of muscle strength and lower extremity motor performance.

2.2. Muscle strength measurements

A handheld dynamometer (mTas-F1, Anima Corp., Tokyo, Japan) was used to evaluate bilateral isometric knee extension strength as an indicator of overall lower limb strength. Each participant sat upright in an elevated chair with the hips and knees bent at approximately 90 degrees, the feet over the floor, and the palms resting on their thighs. The dynamometer was placed perpendicular to the leg, just above the ankle. During all tests, the dynamometer was stabilized by the examiner's hands and a belt. The participants were instructed to straighten their knees, push the dynamometer, and gradually increase force with maximum voluntary effort; this was maintained for an additional 5 seconds.

During the session, each participant was given consistent verbal encouragement. The dynamometer was stabilized by the examiner using both hands during all tests, and the extension of each limb was evaluated. The starting limb was randomized. Leg strength was measured twice, and the mean was used as a parameter.[1,26] Bilateral knee extension forces (kgf) were normalized against body weight (kgf/kg), and muscle strength measurements were used to predict lower extremity motor performance.

2.3. Walking time assessment

To assess the minimum walking time, participants were asked to walk 5 m straight at their maximum speeds[11]; the run-up distance was set to 3 m, and the time required for the patient to cross 5 m (determined from the start reference line, to crossing the goal reference line) was measured. The participants were instructed to stand still with their feet behind a taped starting line and walk in a straight line at their maximum speed, without stopping at the goal reference, following the examiner's "Go!". Timekeeping started at the first foot fall and ended when the participant's first foot completely crossed the 5 m end line.[31]

2.4. Timed Up & Go test

The participants started in the chair sitting position, while the distance to the pole was 3 m. They walked as fast as possible, went around the pole, and sat back in the chair. The examiner measured the time required to return to the chair sitting position from the start; the use of walking aids, such as a cane, handrail, walker, or orthosis, was not permitted.

2.5. Data analysis

We predicted that lower extremity motor performance would be linearly or logarithmically affected by bilateral lower muscle strength.[32] Therefore, a functional model based on strength and performance was constructed as follows:

$$fx(x) = \beta_s x_s + \beta_w x_w + \alpha + \varepsilon \tag{1}$$

$$fx(x) = \beta_s \ln x_s + \beta_w \ln x_w + \alpha + \varepsilon \tag{2}$$

where β is the contribution ratio for the weak (w) or strong side (s) of the leg; x is the normalized knee extension strength; α is the potential effect of confounding factors; and ε is the residual error. Each participant's data were fitted to the model via the least-squares method. The Akaike information criterion (AIC) matrix was used to assess the compatibility of the α- and β-values of the model on the weak and strong sides of the leg. The AIC was calculated as follows:

$$AIC = n\,log\left(\frac{SSR}{n}\right) + 2k \tag{3}$$

where n is the number of data entries, SSR is the sum of squared residuals between the model's predictions and actual data, and k is the number of parameters. A lower AIC value indicates better α- and β-values of the model.[33] If the model was applicable, the series of values for ε in Eqs. (1) and (2) would be uncorrelated to each other (i.e., independent); therefore, we assessed the applicability of the model with the Ljung–Box test to measure the independence of ε as a white noise and residuals process. The following equation was used for the Ljung–Box test:

$$Q(h) = n(n+2)\sum\nolimits_{i=1}^{h} \frac{\hat{\rho}_l^{\,2}}{n-i} \tag{4}$$

where n is the sample size, $(\hat{\rho}_l)$ is the sample autocorrelation at lag i, and h is the number of lags being tested. Thus, the data permitted the evaluation of whether lower extremity motor performance is linearly or logarithmically affected by bilateral lower muscle strength. We defined statistical significance as $P < .05$; all statistical tests were performed using R 3.4.0 software (R Foundation for Statistical Computing, Vienna, Austria).

3. Results

In total, 121 community-dwelling individuals (sex, 46 male and 75 female individuals) were recruited (Table 1). The participants' age ranged from 32 to 86 years (average, 67.1 years; standard deviation [SD], 10.8 years). Their body weight ranged between 36.9 and 82.5 kg (average, 57.3 kg; SD, 9.4 kg), and the body mass index was between 15.6 and 31.8 (average, 22.8; SD, 2.8). The normalized knee extensor strength on the strong side for the 121 participants in this study ranged from 1.40 to 8.56 kgf/kg (average, 5.39; SD, 1.30 kgf/kg); the normalized knee extensor strength on the weak side ranged from 1.21 to 8.26 kgf/kg (average, 4.89; SD, 1.27 kgf/kg).

Table 1

Characteristics of the study population.

	Participants (n = 121)
Age (years)	67.1 ± 10.8
Sex (male/female)	46/75
Body weight (kg)	57.3 ± 9.4
Body mass index (kg/m^2)	22.8 ± 2.8
Normalized knee extensor strength on the strong side (kgf/kg)	5.39 ± 1.30
Normalized knee extensor strength on the weak side (kgf/kg)	4.89 ± 1.27

Values are presented as means ± standard deviations.

Figure 1 shows the AIC matrix calculated to determine optimal α-, β_s-, and β_w-values for the linear and logarithmic models. The smallest AIC value for the linear model (–182.71) was lower than that for the logarithmic model (–156.06) regarding the walking

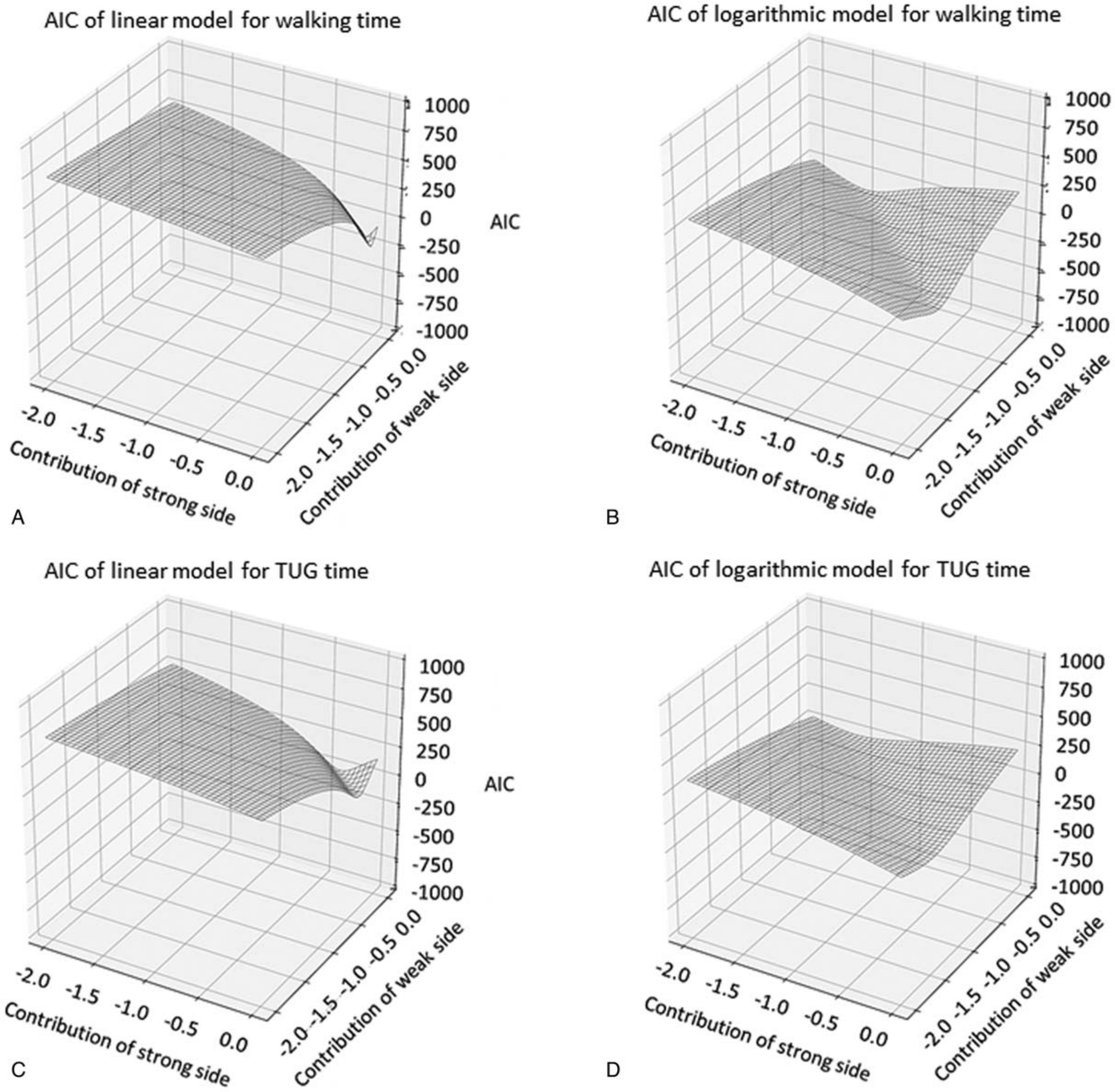

Figure 1. The AIC matrices for walking (A and B) and TUG performance (C and D) times were determined to ascertain the optimal α-, β_s-, and β_w-values for the linear and logarithmic models. AIC = Akaike information criterion, TUG = Timed Up & Go.

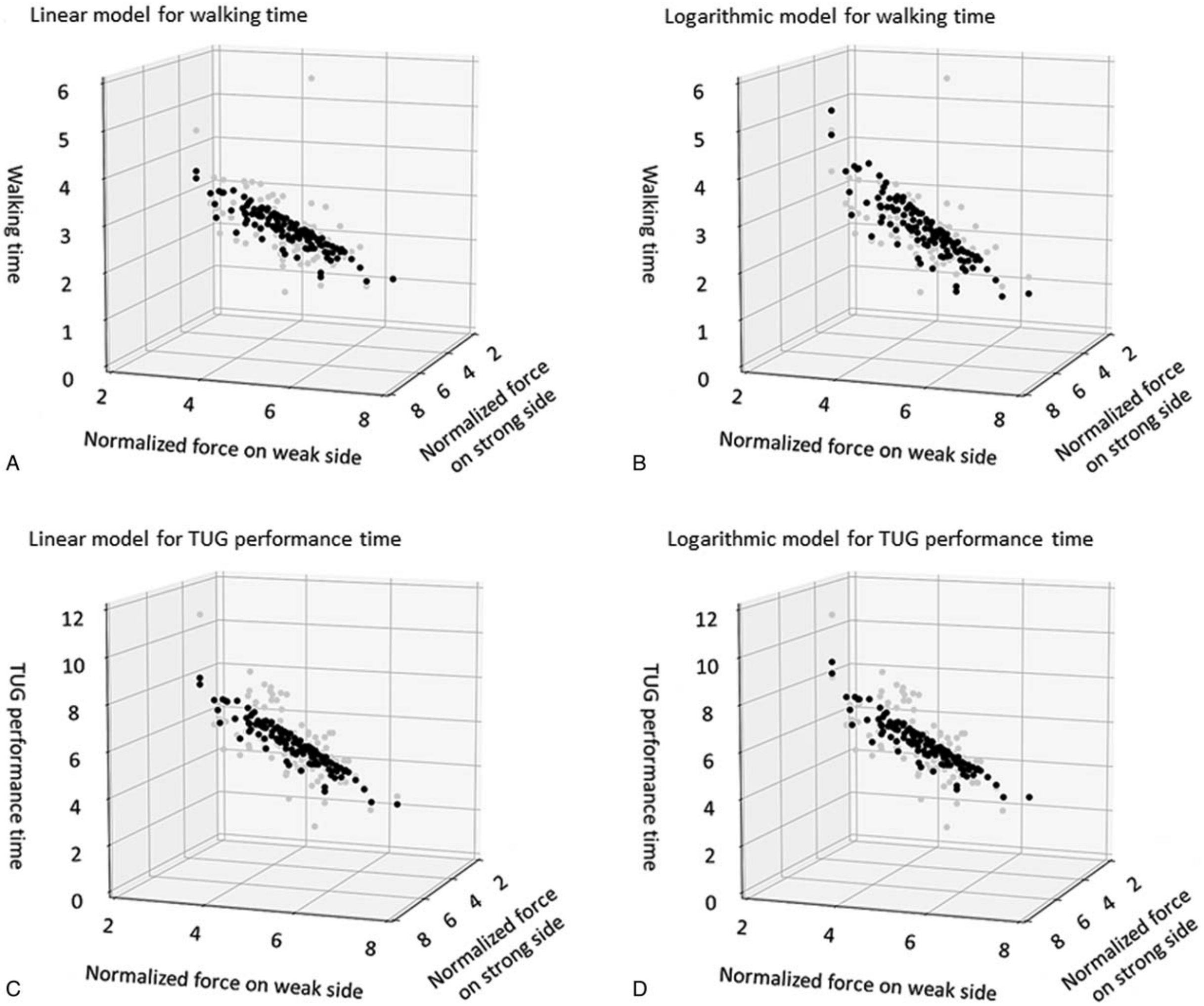

Figure 2. Scatter plot showing the relationship between the measured and predicted walking times (A and B) and the TUG performance time (C and D). The predicted values were derived from linear and logarithmic model equations using optimal α-, β_S-, and β_W-values. Gray and black circles represent actual and predictive data, derived from the linear and logarithmic models, respectively. TUG = Timed Up & Go.

time; however, the smallest AIC value was lower for the logarithmic (–19.0.6) than for the linear model (–16.49) regarding the Timed Up & Go (TUG) performance time. Figure 2 shows the scatterplots for the relationship between the actual and predicted walking times, and the TUG performance time. The predicted values for the walking and TUG performance times were derived from the linear and logarithmic model formulae using optimal α-, β_s-, and β_w-values; the linear and logarithmic models were similar to both the actual walking and TUG performance times obtained. The Ljung–Box test showed that the series of ε-values for the model with the lowest AIC was independent in the linear and logarithmic models, indicating that both models were efficient ([walking time] linear model: $P = .329$, logarithmic model: $P = .220$; [TUG performance time] linear model: $P = .165$, logarithmic model: $P = .104$).

In the linear model for walking time estimation, the $|\beta_s|$-value (0.11) was larger than the $|\beta_w|$-value (0.00). This finding indicated that the muscle force on the strong side of the leg contributed more to the walking time compared to the weak side of the leg. In the logarithmic model's TUG performance time estimation, $|\beta_w|$-value (1.00) was also larger than $|\beta_s|$-value (0.52), indicating that muscle force on the weak side of the leg contributed more to the TUG performance time compared to that on the strong side of the leg.

4. Discussion

In this study, a correlation between both legs' muscle strengths and lower extremity motor performance—including walking and TUG performance times—was discovered by applying linear and logarithmic regression modeling. The results indicated that the correlation between the knee extension strength and the walking time was linear on the strong side, whereas that between the TUG performance time and the knee extension strength was logarithmic on the weak side.

The slowing of lower extremity motor functions, such as walking and sit-to-stand transfer, is likely to cause a decline in activities of daily living performance capacity,[34] and may increase fall risk[35] and mortality.[24] Previous studies have noted that the knee extension strength was associated with better lower extremity motor performance.[28,29,36] Cross-sectional studies on strength and function have focused on correlational analysis using linear regression modeling[28,29,36,37]; however, some reports have demonstrated that lower extremity muscle strength was linearly related to the walking speed[37] and the TUG performance time,[38] whereas others have reported that no correlation was found.[37] The lack of a linear relationship between lower extremity motor performance and strength likely contributes to the discrepancies regarding the correlation between lower limb muscle strength and lower extremity motor performance in the literature.[37]

A previous study regarding the relationship between function and strength noted that the knee extension strength was correlated to non-linear function with a threshold for lower extremity functions[29]; the threshold level was 0.6 Nm/kg for walking and 0.8 to 1.2 Nm/kg for transferring to the bed/toilet/shower.[39,40] In our study, the correlation between the walking time and strength resembled linear modeling, whereas the relationship between the TUG performance time and strength resembled logarithmic modeling. Different models for walking and TUG may have been caused by the lower threshold level for walking than for sit-to-stand transfer. In our work, the participants' knee extension strengths were slightly high, as they were community-dwelling people without palsy or injury; therefore, many participants' knee extension strengths may be above the threshold level for walking. While this leads to the linear relationship between walking and strength, the threshold level for sit-to-stand transfer may be higher than many participants' knee extension strengths; therefore, the relationship between the TUG and knee extension strength resembled the logarithmic model. Correspondingly, our results showed that knee extension strength on the strong side predicted walking time more accurately than the weak side; conversely, that on the weak side predicted TUG performance time more accurately than the strong side because of the lower threshold level for walking than for sit-to-stand transfer.

Interestingly, a previous study reported that 88% of the variability in walking speed was not explained by isometric strength; therefore, strength is an important—but not comprehensive—determinant of walking.[41] In fact, the mode of isometric evaluation was not the same as for lower extremity performance; thus, the use of isometric measurements using a handheld dynamometer seems to be limited by the lack of specific rhythmic (walking) and isotonic (sit-to-stand transfer) performance. Future studies are needed to evaluate whether changes in isometric and isotonic muscle strength values are reflected in the ability of the participants to walk and transfer from a sitting to standing position. Additionally, a previous study noted that hip extensor strength predicted walking performance, whereas ankle plantar flexion strength predicted older adults' maximal walking speed and stride length[7]; further research is needed to investigate the relationship between strengths of multiple muscle groups and lower extremity performance, which may yield a more comprehensive assessment of total body strength than a single joint assessment.

In conclusion, this study presented a different model that reflects the relationship between muscle strength of both legs and lower limb performance times, such as gait and TUG performance. Resistance training based on normalized knee extensor strength is necessary to improve muscle strength and prevent functional decline. The findings of this study may contribute to an evidence-based approach to resistance training for lower extremity motor performance.

Author contributions

Study concept and design: Kilchoon Cho, Makoto Suzuki.
Acquisition of participants and data: Kilchoon Cho, Naoki Iso, Takuhiro Okabe, Hiroshi Goto, Keisuke Hirata, Junichi Shimizu.
Analysis and interpretation of data: Makoto Suzuki, Kilchoon Cho. Preparation of manuscript: Makoto Suzuki, Kilchoon Cho.
Conceptualization: Kilchoon Cho, Makoto Suzuki.
Data curation: Kilchoon Cho, Naoki Iso, Takuhiro Okabe, Hiroshi Goto, Keisuke Hirata, Junichi Shimizu.
Formal analysis: Kilchoon Cho, Makoto Suzuki.
Visualization: Kilchoon Cho, Makoto Suzuki.
Writing – original draft: Kilchoon Cho, Makoto Suzuki.
Writing – review & editing: Kilchoon Cho, Makoto Suzuki, Naoki Iso, Takuhiro Okabe, Hiroshi Goto, Keisuke Hirata, Junichi Shimizu.

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