Foot Forces Induced Through Tai Chi Push-Hand Exercises

Shiu Hong Wong,¹ Tianjian Ji,¹ Youlian Hong,²,³ Siu Lun Fok,⁴ and Lin Wang³,⁵
¹University of Manchester; ²Chengdu Sports University; ³Chinese University of Hong Kong; ⁴University of Minnesota; ⁵Shanghai University of Sport

The low impact forces of Tai Chi push-hand exercises may be particularly suited for older people and for those with arthritis; however, the biomechanics of push-hand exercises have not previously been reported. This paper examines the ground reaction forces (GRFs) and plantar force distributions during Tai Chi push-hand exercises in a stationary stance with and without an opponent. Ten male Tai Chi practitioners participated in the study. The GRFs of each foot were measured in three perpendicular directions using two force plates (Kistler). The plantar force distribution of each foot was measured concurrently using an insole sensor system (Novel). The results showed that the average maximum vertical GRF of each foot was not more than 88% ± 6.1% of the body weight and the sum of the vertical forces (103% ± 1.4%) generated by the two feet approximately equals the body weight at any one time. The horizontal GRFs generated by the two feet were in the opposite directions and the measured mean peak values were not more than 12% ± 2.8% and 17% ± 4.3% of the body weight in the medio-lateral and antero-posterior directions respectively. Among the nine plantar areas, the toes sustained the greatest plantar force. This study indicates that push-hand exercises generate lower vertical forces than those induced by walking, bouncing, jumping and Tai Chi gait, and that the greatest plantar force is located in the toe area, which may have an important application in balance training particularly for older adults.

Keywords: ground reaction forces, plantar force distribution, biomechanics

For older people, Tai Chi exercises may be particularly suitable owing to their slow, smooth and flowing movements, requiring a high level of concentration and whole body coordination.¹ Thus, Tai Chi has been considered as an appropriate exercise for older adults. Studies found that older long-term Tai Chi practitioners demonstrated better postural balance when standing on a static²,³ or on a perturbed platform.⁴,⁵ Tai Chi was also found to improve balance and reduce the risk of falls in the older adult population.⁶,⁷ Tai Chi exercises contain two main categories: Tai Chi Chuan and Tai Chi push-hand. Compared with Tai Chi Chuan’s complicated movements, Tai Chi push-hand involves simple cyclic and articulated motion, and is easy to learn. It can be practiced individually or by two people working together. It can be practiced with a stationary stance (static push-hand), with both feet firmly acting on a flat surface without any stepping, or with moving steps (dynamic push-hand) with movement of both feet.⁸ The four phases of push-hand movement in a cycle are (a) ward off, (b) roll-back, (c) press and (d) push (Figure 1).⁹ During these exercises, the ground reaction forces (GRFs) due to the body weight are shifted between the two feet cyclically.

The biomechanical characteristics of Tai Chi have been studied in some detail. These studies focused on the biomechanical characteristics of some representative Tai Chi movements and Tai Chi gait.⁸,¹⁰–¹² It was noted that the GRFs from Tai Chi gait were smaller than those from walking.¹⁰,¹¹ This indicated that Tai Chi was an appropriate exercise for older people due to the biomechanical characteristics of slow motion with low impact forces. Tai Chi push-hand is an important category of Tai Chi exercises. Specific movement characteristics of Tai Chi push-hand may bring potential benefit for older people and they consist of a few simple movements that are easy to learn. However, the biomechanical characteristics of Tai Chi push-hand exercises have not been studied to date.

The objectives of this study are to determine the biomechanical characteristics of GRFs on two feet in the three perpendicular directions and the plantar force...
distribution of each foot generated by Tai Chi push-hand exercises. The hypotheses of the study are that (1) Tai Chi push-hand exercises produce lower vertical ground forces than Tai Chi gait and (2) the large toe (or great toe) is the plantar region that exerts the highest force during the exercise. The results from the study may provide useful information and a scientific basis for using Tai Chi push-hand as a beneficial exercise for older people.

**Method**

Ten male Tai Chi practitioners (age: $44.0 \pm 14.0$ y, height: $163.7 \pm 7.9$ cm, body mass: $70.9 \pm 15.3$ kg, Tai Chi experience: $12.5 \pm 7.5$ y) were recruited from the Yang Style Tai Chi Group in Hong Kong. None of the practitioners had injuries when participating in the study. All the tests were conducted in the biomechanics laboratory at the Chinese University of Hong Kong. Written informed consents were obtained from all participants and the study was approved by the Ethics Committee of the University.

Two force platforms (Kistler 9281, Switzerland) were placed diagonally on a floor. These allowed a participant to place his left foot on the front force platform and his right foot on the back platform comfortably. The signals from the force platforms (GRFs in the medio-lateral [ML], antero-posterior [AP] and vertical directions) were recorded using a computer station with DEWSoft 6.3 (Dewetron Ges.m.b.H, Austria). A sampling frequency of 1000 Hz was adopted throughout. To suppress interfering signals and reduce background noise, Butterworth low-pass filtering was used, with a cutoff value of 30 Hz, to have a maximally flat frequency response.

An insole force sensor system (Novel Pedar-X, Munich) was used to measure the plantar force distribution. As the characteristics of foot ground contact may be affected by the types of footwear, the insoles from the system were worn on both feet with the same types of sock and shoe. The participants had shoe sizes 41–43 (Europe shoe size) and appropriate sizes of insoles were used. Each insole has 99 sensors, and the recorded data were stored in a data-logging box that was attached to the waist of the participant. With the aid of a calibration device (Novel Trublu, Munich), all sensors were calibrated before the tests. The reliability of this system has already been studied.13

A video camera (9800, JVC Inc., Japan) with a sampling frequency of 100 Hz was used to record the movement of the participants. The camera was synchronized with the force plates and the signals from the camera and the platforms were collected on a computer station using DEWSoft 6.3 (Dewetron Ges.m.b.H, Austria). At the start of the data collection, the Pedar-X insole system generated a flash that was captured by the video camera as a synchronization signal for the camera and the insole system. The video images were then used to identify each foot movement of the Pedar-X records which were then used in the data analysis. Four phases of Tai Chi push-hand movements were identified and defined based on a single participant who was an experienced Tai Chi practitioner. With both feet on the force platforms and with the insoles worn, all participants were asked to perform two trials of push-hand exercises, with and without an opponent, at a regular speed. In each trial, five cycles of movement were completed, recorded and analyzed. For reliability and consistency, the same opponent was used to perform the push-hand exercise with each participant. Participants were instructed verbally to perform as naturally as possible. Each participant was given 15 min to warm up and practice before the test.

Time histories for the three-directional GRFs for each foot were recorded. Normalized forces, which were the ratios of the measured forces to the body weights of the participants, were used to unify the analysis. The force-time histories were then processed in the frequency...
domain using Fourier response functions (Matlab manual) to determine the principal frequency of the movement. For the analysis of plantar force distribution, each foot was divided into nine distinct regions: Medial heel (M1), Lateral heel (M2), Medial midfoot (M3), Lateral midfoot (M4), 1st metatarsal head (M5), 2nd metatarsal head (M6), 3rd, 4th and 5th metatarsal head (M7), great toe (M8), and lesser toe (M9). This division is in line with a previous study.14

The mean and standard deviation were calculated for each variable (mean GRFs and mean peak GRFs in the three perpendicular directions) without and with an opponent and for the left and right feet (Table 1). Differences between mean values were determined using non-parametric Mann-Whitney U, and two-tailed significance (alpha $P < .05$) was reported.

**Results**

The vertical GRFs exhibited cyclic patterns for without (Figure 2a) and with (Figure 2b) an opponent during the push-hand movements, the mean maximum vertical GRF of each foot was not more than 88.4% ± 6.1% of the body weight and the mean minimum vertical GRF was not less than 15.1% ± 5.0% of the body weight and the push-hand exercise generate little impact forces (103% ± 1.4% of the body weight). The GRF shifted between the two feet with the forward and backward movements. When the participant pushed forward to his extreme, the left foot generated the maximum vertical force (the peak of the dark line in Figure 2) while the right foot generated its minimum force (the bottom of the gray line in Figure 2). The opposite force distribution was observed when the body moved backward. The sum of the vertical forces of both feet of each participant was almost constant and approximately equal to the body weight at any instant (Figure 2). This observation was supported by the mean vertical GRFs of two feet, 102.5% ± 0.7% and 103.0% ± 1.4% of the body weight for without and with an opponent respectively. A horizontal line representing 0.5 of the normalized vertical GRF crosses the intersection points between the two force curves produced by the two feet (Figure 2). The forces generated by the two feet are observed approximately symmetric about the dashed line at 0.5 (Figure 2). The results showed that this push-hand exercise was a cyclic movement with a single frequency of 0.39 Hz (ie, 0.39 cycle of the movement was completed in 1 s) without an opponent and 0.45 Hz with an opponent. The peaks of forces produced by each foot varied slightly between cycles, but the frequency of movement was relatively constant for each individual. The frequencies of movement for the 10 participants were 0.30 ± 0.08 Hz without an opponent and 0.39 ± 0.07 Hz with an opponent. The results indicated that the frequency of movement varied individually and that the movement became a little faster when the opponent was involved. The mean peak vertical GRF was not significantly different between the left foot (85.2% ± 5.4%) and right foot (88.0% ± 8.2%) without an opponent, and between the left (88.4% ± 6.1%) and right (85.7% ± 12.3%) with an opponent (Table 1). The mean peak force on the left foot was greater with an opponent than without an opponent ($P < .05$). When one foot force reached the maximum, the force in the other foot becomes the minimum. The mean minimum vertical GRF was not less than 15.1% ± 5.0% of body weight (Table 1).

The horizontal forces produced by the left foot were always in the opposite directions to those produced by the right foot, the forces in the two horizontal directions showed a similar pattern of variation and the mean peak values were not more than 12.0% ± 2.8% of the body weight in the ML direction and 16.7% ± 4.3% in the AP direction. The horizontal GRFs generated by the two feet in two sides of the zero-force axis in both ML and AP directions with and without an opponent (Figure 3). In addition, the force curves contain a few harmonics (Figure 3). The horizontal forces in the AP direction were 24–41% larger than those in the ML direction (Table 1). Similar to the vertical forces, the horizontal forces were cyclic but they also contained higher harmonics. The horizontal forces produced with an opponent were larger than those without an opponent, in particular the averaged force for the left foot in the ML direction and the averaged peak force for the right foot in the AP direction.

The combined forces generated by the two feet are added; it led to a single curve for each figure (Figure 4) with a single dominant frequency.

The area of the great toe experienced larger force than any other region of a foot. When pushing forward, the participants had the largest force in the area of the great toe (M8) of the left foot, 18.2% ± 6.7% of the body weight, which is 1.3% larger than the other two forefoot regions (3rd, 4th and 5th metatarsal head [M7] and lesser toe [M9]), whereas the lowest force of 2.6% ± 1.6% occurred in the medial midfoot region (M3) without an opponent (Table 2). The forces increased or remained the same in all regions except the lateral heel (M2) of the left foot with an opponent. When moving backward, the participants had a larger force on the areas of the medial heel (M1) of the two feet.

**Discussion**

This study was aimed to qualitatively characterize the biomechanical features of foot-ground contact during push-hand exercise, in which two feet keep contact with ground while the body moves cyclically with larger movements in the AP direction and smaller movements in the ML direction. The study of the GRF induced by push-hand allows us to compare quantitatively with those generated from other common types of human movement. The results demonstrated that push-hand exercise generated little impact and lower vertical forces than those induced by walking, bouncing, jumping and Tai Chi gait.
Table 1  Mean and mean peak ground reaction forces and standard deviation (% of body weight)

<table>
<thead>
<tr>
<th></th>
<th>ML L</th>
<th>ML R</th>
<th>AP L</th>
<th>AP R</th>
<th>Vertical L</th>
<th>Vertical R</th>
<th>Vertical T</th>
<th>Ratio AP/ML L</th>
<th>Ratio AP/ML R</th>
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<tr>
<td><strong>Mean GRFs</strong></td>
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<td></td>
</tr>
<tr>
<td>Without opponents</td>
<td>6.3 ± 1.9</td>
<td>6.2 ± 1.8</td>
<td>8.7 ± 2.3</td>
<td>8.3 ± 2.3†</td>
<td>53.3 ± 3.1</td>
<td>49.6 ± 3.5</td>
<td>102.5 ± 0.7</td>
<td>1.41 ± 0.23</td>
<td>1.35 ± 0.22†</td>
</tr>
<tr>
<td>With opponents</td>
<td>7.5 ± 2.0*</td>
<td>6.3 ± 1.7†</td>
<td>9.1 ± 2.1</td>
<td>9.5 ± 2.5†</td>
<td>57.2 ± 4.2*</td>
<td>45.6 ± 4.6†*</td>
<td>103.0 ± 1.4</td>
<td>1.23 ± 0.10*</td>
<td>1.51 ± 0.18†*</td>
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<td><strong>Mean Peak GRFs</strong></td>
<td><strong>Mean Minimum GRF</strong></td>
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<td></td>
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<tr>
<td>Without opponents</td>
<td>11.2 ± 3.2</td>
<td>10.6 ± 2.6</td>
<td>15.9 ± 4.3</td>
<td>13.2 ± 3.4†</td>
<td>85.2 ± 5.4</td>
<td>88.0 ± 8.2</td>
<td>—</td>
<td>1.45 ± 0.25</td>
<td>1.26 ± 0.20†</td>
</tr>
<tr>
<td>With opponents</td>
<td>12.0 ± 2.8</td>
<td>11.4 ± 2.8</td>
<td>16.0 ± 3.2</td>
<td>16.7 ± 4.3†*</td>
<td>88.4 ± 6.1*</td>
<td>85.7 ± 12.3</td>
<td>—</td>
<td>1.35 ± 0.18</td>
<td>1.46 ± 0.17†*</td>
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Note: L: left foot; R: right foot; T: two feet; ML: medio-lateral direction; AP: antero-posterior direction; Vertical: vertical direction.

†P < .05, left foot vs right foot in same direction.

*P < .05, without an opponent vs with an opponent in same leg.
The vertical GRFs with and without an opponent (Figure 2) have the following characteristics: (1) the peak force for each foot is always less than the body weight; (2) the movement of push-hand is dominated by a single frequency; (3) the forces generated from the two feet are almost symmetric to the horizontal line at 0.5 of the body weight; (4) the force produced by the left foot has a phase difference of 180 degrees (π radians) to that of the right foot; and (5) the sum of the forces generated by the two feet is almost a constant and equals the body weight, although the forces from each foot are functions of time. The first characteristic shows that no foot leaves the ground during the exercise while the second, third and fourth characteristics indicate that push-hand exercise is a smooth cyclic movement. The fifth means that push-hand exercise is a relatively gentle movement.

The vertical GRFs produced from push-hand exercises were smaller than those of other physical activities, such as Tai Chi gait and walking. Mao et al.10 showed that the amplitudes of the vertical GRFs of each foot in performing five representative Tai Chi movements were significantly lower than those in normal walking. Wu and Hitt11 found that the vertical GRF in performing Tai Chi gait reached a peak value of 109.0% ± 2.0% of body weight. When people bounce with music, as observed at pop concerts, the peak force generated is between 1.3

Figure 2 — Normalized vertical forces on two feet and the sum of the forces. (a) Without an opponent, (b) with an opponent.
Figure 3 — Normalized horizontal forces on two feet. (a) AP forces of left and right feet without an opponent. (b) ML forces of left and right feet without an opponent. (c) AP forces of left and right feet with an opponent. (d) ML forces of left and right feet with an opponent.

Figure 4 — Sum of the normalized horizontal forces on both feet. (a) AP forces without an opponent. (b) ML forces without an opponent. (c) AP forces with an opponent. (d) ML forces with an opponent.
<table>
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<tr>
<th></th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
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<th>M6</th>
<th>M7</th>
<th>M8</th>
<th>M9</th>
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<td><strong>Without opponent</strong></td>
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<tr>
<td>Left foot</td>
<td>16.2 ± 3.9</td>
<td>13.5 ± 5.5</td>
<td>2.6 ± 1.6</td>
<td>10.4 ± 4.7</td>
<td>8.7 ± 2.5</td>
<td>13.8 ± 2.8</td>
<td>16.9 ± 3.9</td>
<td>18.2 ± 6.7</td>
<td>16.9 ± 7.1</td>
</tr>
<tr>
<td>Right foot</td>
<td>15.6 ± 4.9</td>
<td>10.0 ± 4.2</td>
<td>5.1 ± 1.4</td>
<td>11.6 ± 5.5</td>
<td>10.0 ± 5.1</td>
<td>13.6 ± 4.4</td>
<td>14.6 ± 6.2</td>
<td>12.6 ± 5.0</td>
<td>9.0 ± 4.3</td>
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<td><strong>With opponent</strong></td>
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<tr>
<td>Left foot</td>
<td>16.4 ± 4.7</td>
<td>13.2 ± 4.4</td>
<td>3.0 ± 1.6</td>
<td>11.5 ± 4.9</td>
<td>8.7 ± 2.9</td>
<td>13.8 ± 3.0</td>
<td>17.7 ± 5.2</td>
<td>18.3 ± 5.7</td>
<td>18.2 ± 6.7</td>
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<tr>
<td>Right foot</td>
<td>15.2 ± 8.0</td>
<td>10.5 ± 5.5</td>
<td>5.1 ± 2.0</td>
<td>10.1 ± 6.4</td>
<td>8.8 ± 3.9</td>
<td>12.6 ± 5.2</td>
<td>13.7 ± 6.2</td>
<td>10.3 ± 3.2</td>
<td>7.1 ± 4.7</td>
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and 1.7 times body weight depending on the frequency of movement. Repetitive jumping leads to even higher GRFs between 2.5 and 3.5 times body weight depending on the height of jumping. The vertical foot forces generated from Tai Chi gait, walking, bouncing, jumping and push-hand exercises are all functions of time and are cyclic. However, during push-hand exercises the center of mass of the body remains at almost the same height, and this does not cause obvious changes of the velocity of the participant’s body in the vertical direction. Thus, minimal inertial forces are generated in the vertical direction, resulting in vertical GRFs that approximately equal the body weight (103.0% ± 1.4%). The normalized maximum vertical forces generated by different human movements were compared (Figure 5), where the dark bars show the force magnitudes induced by one foot and the gray bars by two feet. It can be seen that the forces generated by push-hand exercises are the lowest in the comparison group (Figure 5).

It has been suggested that Tai Chi is a safe weight-bearing exercise and may be suitable even for patients who suffer from rheumatoid arthritis. The push-hand exercises with a stationary stance are simpler than Tai Chi exercises and generate little impact forces on the two feet. Thus, static push-hand exercises may be an alternative to Tai Chi exercises and may particularly benefit older people.

A cyclic pattern was found for the forces in both AP and ML directions. In previous studies, the horizontal GRFs during any kind of Tai Chi exercise have not been reported. Moreover, the maximum reaction forces were 12% and 17% of the body weight in the AP and ML directions. When the forces induced by the two feet in the two perpendicular horizontal directions are added for the exercise without and with an opponent, the combined forces are dominated by a single frequency (Figure 4). The dominant frequency is the same as that for the corresponding vertical forces.

The horizontal forces produced by the left foot were in the opposite directions to those produced by the right foot (Figure 3), whereas the vertical forces applied by the two feet were in the same direction (Figure 1). The two feet were placed apart slightly more than the width of shoulder in the ML direction and about 1.5 times the width of shoulder in the AP direction in the stance of the push-hand exercise. When standing still in such a stance, the horizontal forces applied by the left foot would be in the outward and forward directions, while those by the right foot, in the outward and backward direction. In other words, the forces generated by the two feet are opposite in both AP and ML directions, which satisfies equilibrium conditions. When the body moved forward during the exercise, the left knee bent further and moved forward which produced the forward and outward forces on the ground while the right leg stretched by applying backward and outward forces on the ground to assist the body moving forward.

The sum of the forces on the two feet had the maximum magnitude when the participant was in his most forward or most backward position. They were zero when the center of mass was in the middle of the stance. This happened twice during each cycle of motion. The individual forces from the two feet at these instances were nonzero; in fact, they were equal but in opposite directions. In all other positions, depending on the direction of movement, the forces in one foot would be greater than those in the other to provide a nonzero net force to respond to the movement. The larger forces generated in the AP direction (Table 1) can be explained by the fact that the body has larger movement in the AP direction.

![Figure 5](image_url) — Comparison between normalized maximum vertical forces generated from different exercises/movements.
than that in the ML direction, which leads to larger change of velocity in the AP direction. In the exercise with an opponent the force in the AP direction became more significant than that in the ML direction and the right foot generated a larger force. The latter indicates that the players were relying more on the right leg to generate power to combat their opponent. The right leg would receive slightly more work in both strength and movement control in the push-hand exercise.

The ratio of the mean GRF in the AP direction to that in the ML direction is similar to that of the mean peak GRF both with and without the opponent (last column in Table 1), although there are obvious differences between the mean GRFs and the mean peak GRFs.

The combination of the forces in the two horizontal directions for each foot was also examined, but it did not reveal any particular characteristics. When the forces in the three perpendicular directions are combined for each foot, it shows that the pattern of the forces was similar to that of the vertical forces. This is because the vertical forces are far larger than these in the two horizontal directions.

The plantar peak force was located in the region of the toes of the left foot when participants shifted body weight forward while performing the ward-off and push, and on the medial heel region of the right foot when they shifted body weight backward while performing the rollback and press. The results coincide with the findings in the average vertical force and average peak vertical force of this study. The results were also qualitatively similar to the findings from other researchers,10,11 who reported that one of the main forces in Tai Chi gait movements occurred in the region of the great toe. These are different from walking in which the force was maintained in the third metatarsal head region. Tanaka et al.18,19 demonstrated that the great toe and the forefoot played an important role in both feedback and muscle activity of the toe for maintaining balance control. Nurse and Nigg20,21 found that there was an inverse relationship between plantar forces and the joint angles. A combined analysis of kinematics, EMG, and kinetics (GRFs and plantar force distribution) would provide a clearer picture of how the body balance could be controlled during the exercise. All participants had several years of experience of Tai Chi. It would be useful to examine the same exercises for non-Tai Chi participants and compare the forces characteristics for the two groups. The participants in this study were relatively young with an average age of 44 years. Further work should include older participants with ages over 65 years. No measurements of walking were conducted. The ground reaction forces and plantar pressure of walking collected in the same way with the same equipment for the same participants would allow better comparison between push-hand and walking and also can be used for comparison with previously published data.

This study has revealed unique characteristics of the GRFs produced during push-hand exercises. Firstly, the sum of the vertical forces generated by the two feet in the exercise is approximately equal to the body weight of the participant at any time. This is different from other human periodical movements, such as walking, bouncing, jumping and Tai Chi gait. The averaged peak vertical force on each foot had a mean value no more than 89% of the body weight. The peak vertical forces on either single foot or both feet are smaller than those of the other human movements. Secondly, the averaged maximum forces in the AP and ML directions on each foot are not more than 17% and 12% of the body weight respectively and the sums of the horizontal forces generated in the AP and ML directions for each foot showed a simple harmonic variation with a dominant single frequency that was the same as that in the vertical direction. However, the individual horizontal forces from each foot contained higher harmonics.

This study also supports two hypotheses that push-hand exercises produce even lower vertical ground force than Tai Chi gait and that the great toe is the region that exerts a higher force onto the ground than the other regions of the foot during forward motion. The vertical force produced from push-hand exercises is lower than most typical human movements, such as walking, bouncing, jumping and Tai Chi gait.

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