Postural optimization during functional reach while kneeling and standing

HIROYUKI FUJISAWA, PT, PhD1), HIROTO SUZUKI, PT, PhD2), SHINGO KAWAKAMI, PT, MS2),
KENICHI MURAKAMI, PT, MS2), MAKOTO SUZUKI, PT, PhD3)

1) Department of Rehabilitation, Faculty of Medical Science and Welfare, Tohoku Bunka Gakuen
University: 6-45-1 Kunimi, Aoba-ku, Sendai 981-8551, Japan

Abstract. [Purpose] The purpose of the present study was to examine the validity of functional reach models by comparing actual values with estimated values. [Subjects and Methods] Twenty-eight volunteers were included in this study (male: 14, female: 14, age: 21 ± 1 years, height: 166.8 ± 9.0 cm, and body mass: 60.1 ± 8.5 kg). The maximum forward fingertip position and joint angles were measured using the original equipment. In addition, the maximum forward fingertip position, shoulder joint angle, and knee or ankle joint angle were estimated using the functional reach model. [Results] The correlation coefficients between actual data and estimated data for the maximum forward fingertip position, shoulder joint angle, and ankle joint angle while standing were 0.93, 0.83, and 0.73, respectively. The correlation coefficients between actual data and estimated data for the maximum forward fingertip position, shoulder joint angle, and knee joint angle while kneeling were 0.86, 0.81, and 0.72, respectively. [Conclusion] The validity of both functional reach models in estimating optimal posture was confirmed. Therefore, the functional reach model is useful for evaluation of postural control and optimal postural control exercises.

Key words: Functional reach, Optimization, Kneeling

INTRODUCTION

Functional reach (FR) is a very important motion because it is often performed in daily life. Furthermore, FR is used to evaluate postural control1–5). Duncan et al. developed the FR test to evaluate the limits of stability1). FR distance is reportedly correlated with the center of pressure (COP) excursion2); COP was used as the operational definition of center of gravity (COG).

However, Jonsson et al. found no significant correlation between the reach distance and COP6). Therefore, Fujisawa et al. developed an FR model and clarified the optimal posture that could move the fingertip farthest forward while standing7). The simulation showed that when the height was 170 cm, a postural change could elicit a reach of approximately 25 cm during FR, without moving COG forward. In addition, the maximal FR (FRmax) increased in proportion to height. Increase in foot length proportional to height and COG movement was important for this increase. In addition, with a fixed COG, the relationship between the joint angles of each FRmax did not depend on height.

During rehabilitation, patients are often trained in the kneeling position8), as this possibly strengthens the ability of hip joint control. Although patients can move COP to the front of the ankle joint while standing, they are unable to move COP to the front of the knee joint while kneeling. Therefore, reaching forward while maintaining balance in the kneeling position is difficult.

During FR, the reach position is not decided uniquely for any COG. This is because the number of degrees of freedom of the reaching task is at least 3 in comparison to the 2-dimensional sagittal plane. If the optimal posture for maximum reaching forward can be estimated, it can be applied to the practice of physical therapy, i.e., using FR models, postural control and...
optimal postural control exercises can be evaluated by referring to the estimated values.

The purpose of the present study was to examine the validity of the FR models by comparing actual values with estimated values.

SUBJECTS AND METHODS

Twenty-eight volunteers participated in this study (males: 14, females: 14, age: 21 ± 1 years, height: 166.8 ± 9.0 cm, and body mass: 60.1 ± 8.5 kg), all of whom provided written informed consent prior to participation; the Human Subjects Ethics Committee of Tohoku Bunka Gakuen University approved the study (No. 15-03).

An algorithm was developed to identify optimal posture during FR with a 4-segment geometric model. In this model, optimal posture is adopted to maximize FR, and the movement taken to adopt such a posture is referred to as postural optimization. The segments of the FR model for standing (FR model-s, Fig. 1) consisted of the unilateral upper extremity (reaching arm), the head, unilateral arm, and trunk (HAT), and the 2 lower extremities (i.e., thigh, leg, and foot). The angles of the generalized coordinate system $\alpha$, $\beta$, and $\gamma$, as well as other parameters, were used as variables (Fig. 1). In addition, the origin of the coordinate was set at the ankle joint. Both $\alpha$ and $\gamma$ were calculated by knowing $\beta$ and $G_x$ (the COG position) (Appendix 1). As a result, the optimal posture for the farthest reach possible and the maximum forward fingertip position $FT_{xmax}$ was decided. The FR model for kneeling (FR model-k, Fig. 2) consisted of the unilateral upper extremity (reaching arm), the head, unilateral arm, and trunk (HAT), and the 2 lower extremities (i.e., thigh, leg, and foot). The origin of the coordinate was set at the knee joint in the FR model-k (Fig. 2). Both $\alpha$ and $\gamma$ were calculated by knowing $\beta$ and $G_x$, as in the FR model-s (Appendix 2). As a result, we were able to determine the optimal posture for the farthest reach possible and $FT_{xmax}$. In addition, we referred to the anthropometric data by Winter\(^9\).

$FT_{xmax}$ was simulated with an original program by using MATLAB (2014b, MathWorks, Japan). The height was set to 150, 160, 170, 180, and 190 cm. In the FR model-s, $G_x$ changed from 0% to 60% of the foot length and $\beta$ from 0° to 70°. In the FR model-k, $G_x$ changed from 0 cm to −10 cm and $\beta$ from 0° to 70°. For FR model-s, a Martin-type anthropometer and goniometer was used to measure $l_1$ (trochanter-malleolus distance), $l_2$ (distance between the acromion and the greater trochanter), $l_3$ (upper limb length), $SG$ length (distance between the clavicular head and the acromion), and $SG$ range of motion (ROM) (flexion of the shoulder girdle). For FR model-k, a Martin-type anthropometer and goniometer was also used to measure $l_1$ (lower leg length), $l_2$ (thigh length), $l_3$ (distance between the acromion and the greater trochanter), $l_4$ (upper limb length), $SG$ length (distance between the clavicular head and the acromion), and $SG$ ROM (flexion of the shoulder girdle).

Actual $FT_{xmax}$ was measured using original equipment. For measurement of the joint angle, a tape marker was affixed to the acromion, greater trochanter, lateral epicondyile of the femur, and lateral malleolus. The subjects stood on a tag tile sensor (Huge-MAT, Nitta, Japan) for COP measurement, which was used as an operational definition of COG. The sampling frequency was 8 Hz. The lateral malleolus while standing or the lateral epicondyile of the femur while kneeling was also matched to zero position of the original equipment (Fig. 3). The subjects reached forward with the dominant upper extremity, which was defined as the side used for holding chopsticks. Based on a simulation, the subjects were instructed in the standing position reach as follows: 1) do reach as far forward as possible, 2) do raise your arm higher than your ear, and 3) do not
pull your buttocks backward. The subjects were also instructed in the kneeling position reach as follows: 1) do reach as far forward as possible, 2) do raise your arm higher than your ear, and 3) do pull your buttocks backward slightly. The FR motion was also recorded using a digital video camera (iVIS- HV30, Canon, Japan). The data were used for analysis of joint angles. The COG position (Gx) was measured when the subjects attained maximum forward reach. Moreover, the joint angles were determined using a video analysis system (Dartfish 4.5.2.0, Dartfish, Japan). FTx\textsubscript{max} was estimated using actual Gx and hip joint angle. In addition, actual hip joint angle was used as a restriction condition of \(\beta\). The measurement value was substituted for the segment length: \(\ell_1, \ell_2, \ell_3,\) and \(\ell_4\). The validity of the FR model was considered based on the relationship between actual FTx\textsubscript{max} data and estimated FTx\textsubscript{max} data, and between actual joint angles and estimated joint angles.

Pearson’s product moment correlation coefficient (r) was calculated between the actual FTx\textsubscript{max} and estimated data. The level of significance was p<0.05.

### RESULTS

The actual FTx\textsubscript{max} was 112.1 ± 7.1 cm during FR while standing, and the estimated FTx\textsubscript{max} was 109.3 ± 7.0 cm. The actual shoulder joint angle was 141.5 ± 5.7° and the estimated angle was 136.4 ± 4.8°. The actual ankle joint angle was 0.2 ± 1.7° and the estimated angle was −3.0 ± 1.6°. The correlation coefficients between the actual data and the estimated data for FTx\textsubscript{max}, shoulder joint angle, and ankle joint angle were 0.93 (p<0.01), 0.83 (p<0.01), and 0.73 (p<0.01), respectively (Table 1).

The actual FTx\textsubscript{max} was 90.9 ± 5.9 cm during FR while kneeling, and the estimated FTx\textsubscript{max} was 90.5 ± 6.1 cm. The actual shoulder joint angle was 134.5 ± 8.9° and the estimated angle was 128.6 ± 6.1°. The actual knee joint angle was 110.7 ± 4.5° and the estimated angle was 115.0 ± 3.9°. The correlation coefficients between the actual data and the estimated data for FTx\textsubscript{max}, shoulder joint angle, and knee joint angle were 0.86 (p<0.01), 0.81 (p<0.01), and 0.72 (p<0.01), respectively (Table 1).

### Table 1. FTx\textsubscript{max}, joint angles, and Gx during functional reach

<table>
<thead>
<tr>
<th></th>
<th>FR while standing</th>
<th>FR while kneeling</th>
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<tbody>
<tr>
<td></td>
<td>Actual data</td>
<td>Estimated data</td>
</tr>
<tr>
<td>FTx\textsubscript{max} (cm)</td>
<td>112.1 ± 7.1</td>
<td>109.3 ± 7.0</td>
</tr>
<tr>
<td>Shoulder joint angle (degree)</td>
<td>141.5 ± 5.7</td>
<td>136.4 ± 4.8</td>
</tr>
<tr>
<td>Hip joint angle (degree)</td>
<td>40.1 ± 4.3</td>
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<tr>
<td>Knee joint angle (degree)</td>
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<td></td>
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<tr>
<td>Ankle joint angle (degree)</td>
<td>0.2 ± 1.7</td>
<td>−3.0 ± 1.6</td>
</tr>
<tr>
<td>Gx (cm)</td>
<td>12.0 ± 1.5</td>
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</tbody>
</table>

FR: functional reach; FTx\textsubscript{max}: maximum forward fingertip position; Gx: center of gravity position.

Both actual hip joint angle and Gx were used simulation to estimate FTx\textsubscript{max} and other joint angles.

$\dagger$p<0.01
In results for simulation of FR while standing, FTxmax increased in proportion to height and Gx position (Fig. 4A). When Gx was 60% of the foot length, FTxmax was 103.3 cm at a height of 150 cm and 130.3 cm at a height of 190 cm. Furthermore, when Gx was 60% of the foot length, the optimal posture at 190 cm was 165.1° of shoulder flexion, 60.0° of hip flexion, and 2.5° of ankle plantar flexion. In contrast, when Gx was 0% of the foot length (Gx=0 cm), FTxmax was 87.3 cm at a height of 150 cm and 110.6 cm at a height of 190 cm. Furthermore, when Gx was 60% of the foot length, the optimal posture at 190 cm was 163.0° of shoulder flexion, 68.7° of hip flexion, and 13.8° of ankle plantar flexion.

In the results for simulation of FR while kneeling, FTxmax increased in proportion to height and decreased in proportion to the backward movement of the Gx position (Fig. 4B). When Gx was 0 cm, FTxmax was 89.0 cm at a height of 150 cm and 112.7 cm at a height of 190 cm. Moreover, when Gx was 0 cm, the optimal posture at 190 cm was 158.9° of shoulder flexion, 75.4° of hip flexion, and 113.6° of knee flexion. In contrast, when Gx was −10 cm, FTxmax was 75.2 cm at a height of 150 cm and 99.1 cm at a height of 190 cm. Moreover, when Gx was −10 cm, the optimal posture at 190 cm was 153.6° of shoulder flexion, 82.7° of hip flexion, and 127.1° of knee flexion.

**DISCUSSION**

In this study, the validity of the FR model was clear because the correlation coefficients between actual FTxmax and estimated FTxmax, as well as between the joint angles, were very high. Because ankle joint function decreases in the elderly and in people with disability, these individuals often cannot move Gx far enough forward. Physical therapists have to draw out a patient’s ability to the maximum, and must be able to instruct on the optimal postural control strategy in a given COG...
position. We therefore postulated that the FR model can use not only individual optimization but also general strategic examination.

As an exercise of postural control, FR while kneeling is unique. During FR in the kneeling position, individuals are unable to move Gx forward; however, Gx can be moved forward in the standing position. FTxmax decreases in proportion to amount of backward movement of Gx in the kneeling position. Although FTxmax is the highest when Gx is 0 cm in the kneeling position, it is the lowest when Gx is 0 cm in the standing position. Moreover, we found that when Gx was 0 cm, the optimal posture at 190 cm was 113.6° of knee flexion in the kneeling position and 2.5° of ankle plantar flexion in the standing position. We regard this difference as a type of paradoxical movement. In other words, although individuals who do not pull their buttocks backward are able to reach farther while standing, individuals who pull their buttocks backward can reach farther while kneeling.

Because FTxmax is the highest when Gx is 0 cm in the kneeling position, the gravitational torque at the knee joint is very low during this posture. Therefore, the muscle torque at the knee joint is very low. In contrast, because FTxmax is the highest when Gx is forward in the standing position, the gravitational torque at the ankle joint is very high during this posture. As a result, the plantar flexion muscle torque at the ankle joint is very high. Furthermore, angle β is generally larger in the standing position than in the kneeling position; thus, the gravitational torque at the hip joint is larger in the standing position than in the kneeling position during maximum forward reach. Therefore, the standing position requires greater muscle activity than the kneeling position.

From the viewpoint of balance, the anteroposterior length of the base of support is longer in the kneeling position than in the standing position. However, the maintenance of balance in the kneeling position is very difficult during maximum forward reach because the center of movement of the knee joint is close to the end of the base of support. Postural adjustment is very difficult during maximum forward reach while kneeling because the muscle torque of the knee joint is almost zero, as described above.

In conclusion, the validity of both FR models for estimating optimal posture was confirmed. Therefore, the FR model is useful for the evaluation of postural control and optimal postural control exercises.

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REFERENCES

Appendix 1. FR MODEL-S

The x-coordinate of the center of gravity (COG) is expressed as follows:
\[ Gx = 0.332x_1 + 0.678x_2 \]  (I-1)

However, unilateral upper extremity (reaching arm) weight is included in the weight of HAT (head, arm, and trunk), where,
\[ x_1 = r_1 \sin \alpha \]  (I-2)
\[ x_2 = \ell_1 \sin \alpha + r_2 \sin \beta \]  (I-3)

Using equation I-1,
\[ Gx = 0.332r_1 \sin \alpha + 0.678\ell_1 \sin \alpha + 0.678r_2 \sin \beta \]  (I-4)

Angle \( \alpha \) is transformed equation I-3
\[ \alpha = \sin^{-1} \left( \frac{0.678r_2 \sin \beta + Gx}{0.332r_2 + 0.678\ell_1} \right) \]  (I-5)

The y-coordinate of the fingertip is:
\[ F Ty = \ell_1 \cos \alpha + \ell_2 \cos \beta + \ell_3 \cos \gamma \]  (I-6)

In addition, \( F Ty \) is indicated as follows:
\[ F Ty = \ell_1 + \ell_2 = C \]  (I-7)

Using equation I-5 and I-6,
\[ \gamma = \cos^{-1} \left( \frac{-\ell_1 \cos \alpha - \ell_2 \cos \beta}{\ell_3} \right) \]  (I-8)

\( FTx \) is indicated as follows:
\[ F Tx = \ell_1 \sin \alpha + \ell_2 \sin \beta + \ell_3 \sin \gamma \]  (I-9)

We consider the shoulder-girdle flexion:
\[ F Tx = \ell_1 \sin \alpha + \ell_2 \sin \beta + \ell_3 \sin \gamma + SG \]  (I-10)

Where,
\[ SG = \text{SG length} \times \sin(\text{SG Flexion ROM}) \]  (I-11)
\[ \text{SG length} = Ht \times 0.129, \quad \text{SG Flexion ROM} = 20^\circ \]  (I-12)

In any Gx, we could find both the maximum of \( FTx \) and the optimal posture by operating \( \beta \).

The \( FR_{\text{max}} \) is finally expressed in the next equation.
\[ FR_{\text{max}} = F Tx_{\text{max}} (Gx_{\text{max}}) - \ell_3 \]  (I-13)

In the simulation, we calculated the segment length and the COG position of each segment from height using the following equations.
\[ \ell_1 = 0.491 \times Ht \]  (I-14)
\[ \ell_2 = 0.288 \times Ht \]  (I-15)
\[ \ell_3 = 0.441 \times Ht \]  (I-16)
\[ r_1 = 0.553 \times \ell_1 \]  (I-17)
\[ r_2 = 0.626 \times \ell_2 \]  (I-18)
\[ FL = 0.152 \times Ht \]  (I-19)
\[ C = 0.779 \times Ht \]  (I-20)

Joint angle was calculated using \( \alpha, \beta, \) and \( \gamma \).
\[ \text{ankle} = \alpha \]  (I-21)
\[ \text{hip} = - \alpha + \beta \]  (I-22)
\[ \text{shoulder} = 180 + \beta - \gamma \]  (I-23)
Appendix 2. FR MODEL-K

The x-coordinate of the center of gravity (COG) is expressed as follows:
\[ G_x = 0.122x_1 + 0.200x_2 + 0.678x_3 \]  (II-1)

However, the weight of unilateral upper extremity (reach arm) is included in the weight of HAT, where,
\[ x_1 = -r_1 \]  (II-2)
\[ x_2 = r_2 \sin \alpha \]  (II-3)
\[ x_3 = \ell_2 \sin \alpha + r_3 \sin \beta \]  (II-4)

Using equation II-1,
\[ G_x = -0.122r_1 + 0.200r_2 \sin \alpha + 0.678\ell_2 \sin \alpha + 0.678r_3 \sin \beta \]  (II-5)

Angle \( \alpha \) is transformed equation II-5
\[ \alpha = \sin^{-1} \left( \frac{G_x + 0.122r_1 - 0.678r_3 \sin \beta}{0.200r_2 + 0.678\ell_2} \right) \]  (II-6)

The y-coordinate of the fingertip is:
\[ FT_y = \ell_2 \cos \alpha + \ell_3 \cos \beta + \ell_4 \cos \gamma \]  (II-7)

In addition, \( FT_y \) is indicated as follows:
\[ FT_y = \ell_2 + \ell_3 = C \]  (II-8)

Using equation II-7 and II-8,
\[ \gamma = \cos^{-1} \left( \frac{C - \ell_3 \cos \alpha - \ell_4 \cos \beta}{\ell_4} \right) \]  (II-9)

\( FT_x \) is indicated as follows:
\[ FT_x = \ell_2 \sin \alpha + \ell_3 \sin \beta + \ell_4 \sin \gamma \]  (II-10)

We consider the shoulder-girdle flexion:
\[ FT_x = \ell_2 \sin \alpha + \ell_3 \sin \beta + \ell_4 \sin \gamma + SG \]  (II-11)
\[ SG = SG \text{ length} \times \sin(SG \text{ Flexion ROM}) \]  (II-12)
\[ SG \text{ length} = \text{Ht} \times 0.129, \quad SG \text{ Flexion ROM} = 20^\circ \]  (II-13)

In any \( G_x \), we could find both the maximum of \( FT \) and the optimal posture by operating \( \beta \).
\( FR_{\text{max}} \) is finally expressed in the next equation.
\[ FR_{\text{max}} = FT_{\text{max}}(G_x_{\text{max}}) - \ell_4 \]  (II-14)

In the simulation, we calculated the segment length and the COG position of each segment from the height using the following equations.
\[ \ell_1 = 0.246 \times \text{Ht} \]  (II-15)
\[ \ell_2 = 0.245 \times \text{Ht} \]  (II-16)
\[ \ell_3 = 0.288 \times \text{Ht} \]  (II-17)
\[ \ell_4 = 0.441 \times \text{Ht} \]  (II-18)
\[ r_1 = 0.606 \times \ell_1 \]  (II-19)
\[ r_1 = 0.567 \times \ell_2 \]  (II-20)
\[ r_3 = 0.626 \times \ell_3 \]  (II-21)
\[ C = 0.533 \times \text{Ht} \]  (II-22)

Joint angle was calculated using \( \alpha \), \( \beta \), and \( \gamma \).
\[ \text{knee} = 90 - \alpha \]  (II-23)
\[ \text{hip} = -\alpha + \beta \]  (II-24)
\[ \text{shoulder} = 180 + \beta - \gamma \]  (II-25)