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Abstract

We studied the pressure exerted by hands during push-ups in 21 paraplegic and 2 tetraplegic patients employing 4 different hand positions. In the fingers-spread position, the initial force exerted was a vertical force (Fz), followed by a medio-lateral force (Fy) and then an antero-posterior force (Fx). In the other 3 positions, the order of force type exertion was Fz, Fx, and then Fy. All subjects with neurological injury levels above T4 and subjects between T5 and T10 without spinal instrumentation could not push themselves up in the fingers-spread position. The fact that Fy is initiated before Fx in the fingers-spread position indicates that lateral balancing of the trunk is critical in this position, thus explaining why subjects without spinal instrumentation with neurological injury at a level higher than T10 could not control their spinal columns while performing push-ups. In contrast, antero-posterior balancing takes priority in the other hand positions. We believe that spinal instrumentation helps balance the trunk in the lateral direction, converting the thoracic spine into a rigid body in subjects with neurological injury at levels above T10.

KEYWORDS: spinal-cord-injury, rehabilitation, kinesiology, push-up, floor reaction force

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Original Article

Kinesiological Study of the Push-up Motion in Spinal Cord Injury Patients: Involving Measurement of Hand Pressure Applied to a Force Plate

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We studied the pressure exerted by hands during push-ups in 21 paraplegic and 2 tetraplegic patients employing 4 different hand positions. In the fingers-spread position, the initial force exerted was a vertical force (Fz), followed by a medio-lateral force (Fy) and then an antero-posterior force (Fx). In the other 3 positions, the order of force type exertion was Fz, Fx, and then Fy. All subjects with neurological injury levels above T4 and subjects between T5 and T10 without spinal instrumentation could not push themselves up in the fingers-spread position. The fact that Fy is initiated before Fx in the fingers-spread position indicates that lateral balancing of the trunk is critical in this position, thus explaining why subjects without spinal instrumentation with neurological injury at a level higher than T10 could not control their spinal columns while performing push-ups. In contrast, antero-posterior balancing takes priority in the other hand positions. We believe that spinal instrumentation helps balance the trunk in the lateral direction, converting the thoracic spine into a rigid body in subjects with neurological injury at levels above T10.

Key words: spinal-cord-injury, rehabilitation, kinesiology, push-up, floor reaction force

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The seated position push-up motion consists of the following actions; lifting the body from the floor or seat by extending the elbows from a flexed position, maintaining the elbows in full extension, and then lowering the body smoothly down to the floor or seat by flexing the elbows.

These movements are essential to patients with spinal cord injury (SCI) who have lost their lower extremity functions due to paralysis [1]. For example, push-ups are necessary for the prevention of pressure sores and also for movement from one place to another (wheelchair to car and so on) [1]. If such activities cannot be performed, the patient cannot achieve an independent life style.

Despite the importance of push-ups for the activities of daily life (ADL), there have been few kinesiological studies of this series of motions [2, 3]. We traditionally use 4 different hand positions in exercises for SCI patients: 1) push-ups with a push-up device which provides a strong grip intended mainly for exercise; 2) push-ups with the hand in a clenched (fist) position, which has the advantage of elongating the distance from the floor to the shoulder; 3) push-ups with a flat (palm), providing stable weight support; and 4) push-ups in a spread-finger position to gain more distance than is achievable in the fist position. However, we often encounter SCI patients who cannot perform push-ups using the less stable hand positions. Using a force plate, we investigated the

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pressures exerted by hands of patients doing push-ups; the ability to balance depended upon the location of spinal injury.

Subjects and Methods

Twenty one paraplegic and 2 tetraplegic patients were studied. The neurological level of paralysis was determined according to the ASIA international standard [4]. Subjects' ages ranged from 19 to 51 years (31.4 ± 6.3), their height ranged from 152 to 183 cm (169.0 ± 7.2) and their weight ranged from 41 to 86 kg (57.4 ± 9.1) (Table 1). All subjects required wheelchairs for locomotion and all were able to transfer themselves to and from their wheelchairs without assistance.

The pressures exerted by patients' hands while doing push-ups were measured with a force plate. The apparatus was originally made for gait analysis and consisted of a matrix system (Anima Co. Ltd., Tokyo, Japan). 2 box-shaped, steel-framed platform attachments were designed to augment the gait system. The platforms were set onto the force plate [5].

The subject sat on a rack, and the ischial tuberosities of each subject were set on the same positions on the rack. Their legs and buttocks were placed just outside the force plates (Fig. 1). The subjects carried out push-ups with their hands in the following positions: fist, spread-finger, and palm, and by using the push-up devices firmly attached to the platforms (Fig. 2). The force plate measured reactions exerted against the floor in 3 dimensions while the subjects pushed their bodies away from the floor.

A pair of electrogoniometers was attached to each subject's elbow and wrist joints for the measurement of angular deviation of each joint. The flexion and extension of the elbow joints were measured, and the palmar flexion and dorsal flexion of the wrist joints were measured. The electrogoniometer was made of a flexible steel plate on which 4 strain gauges were attached. A Wheatstone's bridge was assembled from the 4 strain gauges. When the steel plate was flexed, the electric current obtained was in direct proportion to the angular deviation of the joint (Fig. 3). Data from the force plate and electrogoniometers were

Table 1 Subject profiles

No. of subject	Age & sex	Body weight (kg)	Height (cm)	Neurological level	Impairment scale	Etiology	Finger push-up	Spinal instrumentation
1	40 M	77	181	C7	C	Trauma	X	X
2	37 F	41	162	C8	A	Trauma	X	X
3	34 M	86	183	T4	A	Trauma	X	X
4	32 M	50	160	T4	A	Trauma	X	O
5	33 M	63	171	T4	A	Trauma	X	X
6	19 M	57	172	T5	A	Trauma	O	O
7	41 M	49	180	T5	A	Trauma	X	X
8	20 F	63	152	T7	A	Disease	X	X
9	29 M	53	178	T8	A	Trauma	X	X
10	46 M	67	162	T8	A	Trauma	O	O
11	21 F	51	157	T8	A	Trauma	O	O
12	28 M	59	163	T9	A	Trauma	X	X
13	24 M	47	170	T9	A	Trauma	O	O
14	31 M	47	170	T10	A	Trauma	X	X
15	31 M	75	168	T10	A	Trauma	O	O
16	24 M	52	168	T11	A	Trauma	O	O
17	51 M	62	160	T11	A	Trauma	O	O
18	21 M	47	176	T11	A	Trauma	O	X
19	30 M	56	183	T11	A	Trauma	O	O
20	30 M	56	169	T12	A	Trauma	O	O
21	34 M	48	160	T12	A	Trauma	O	X
22	39 M	46	164	T12	A	Trauma	O	O
23	28 M	69	178	L3	A	Trauma	O	O

Finger push-up: o, subject was able to perform push-up; x, subject was unable to perform push-up. Spinal instrumentation: o, subject had undergone spinal instrumentation; x, subject had not undergone spinal instrumentation.

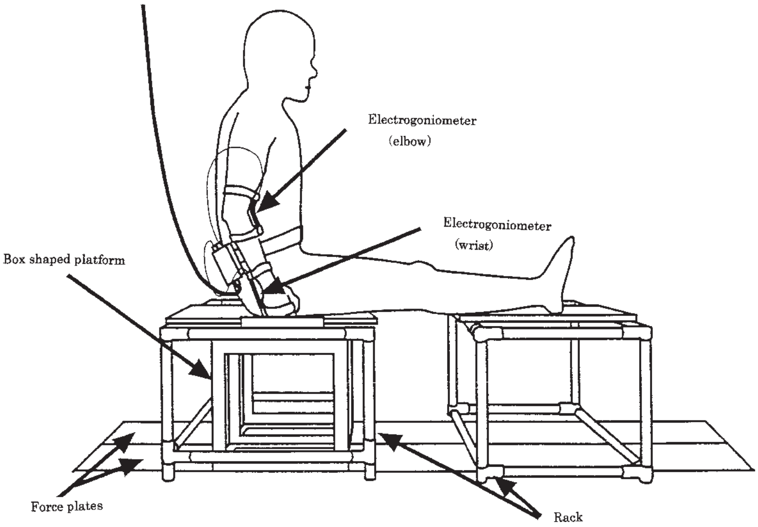

Fig. 1 The force measuring system used in this study.

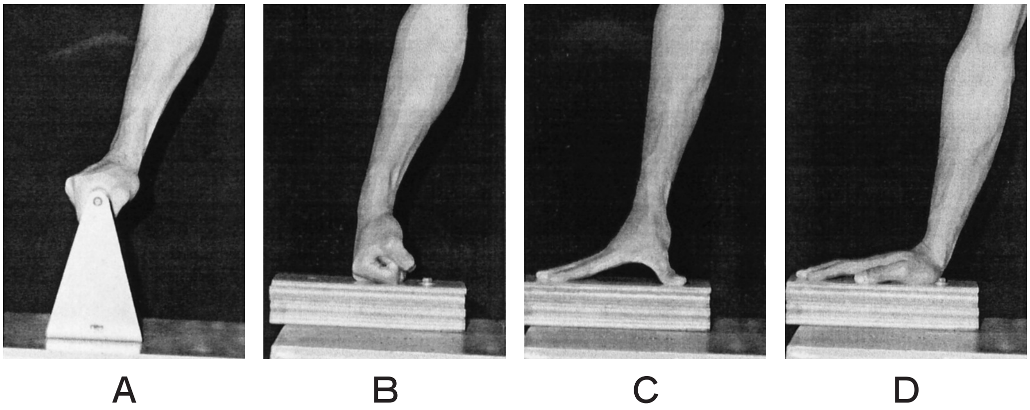

Fig. 2 Four hand positions typically used in exercises for SCI patients.
A, Push-up device; **B**, Fist; **C**, Finger; **D**, Palm.

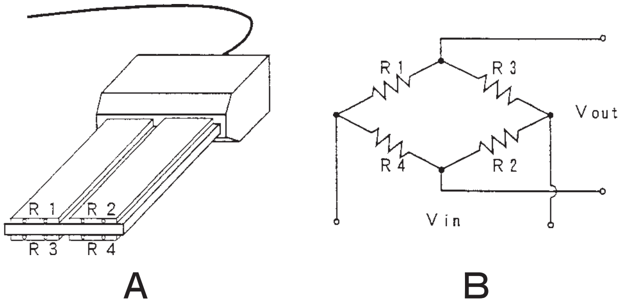

Fig. 3 **A**, Electrogoniometer, to which 4 strain gauges (R1-R4) were installed. **B**, Wheatstone's bridge circuit.

recorded simultaneously on a polygraph.

The subjects were asked to extend their elbows for 1 sec, and to maintain their elbows in this extended position in order to keep their bodies elevated for 1 sec; Then subject were asked to flex their elbows in order to lower their bodies and return to the starting position. A metronome controlled the timing of these motions as precisely as possible.

Results

All patients were able to perform push-ups in the fist and palm positions, and by using the push-up devices. Five patients whose neurological injury levels were at or above T4 could not perform push-ups in the spread-finger position. Eight patients whose neurological injury levels were at or below T11 were able to perform push-ups in the spread-finger position. However, 5 of the 10 patients whose neurological injury levels were between T5 and T10 could not perform push-ups in the spread-finger position. These latter patients had no spinal instrumentation (Table 1).

No essential differences in pressure exerted against the floor or angular deviation of the elbow and wrist joints were observed among the 3 hand positions and the push-up device (Fig. 4). Each component of observed pressure was divided by the subject's body weight, in order to make these components independent of the subject's body weight. The pressures exerted by the hands on the force plate were classified as antero-posterior (AP) force (Fx), medio-lateral (ML) force (Fy), and vertical force (Fz). In all cases, Fz was registered before the initial readings for Fx and Fy. Similarly, Fz continued after the cessation of Fx and Fy in all cases (Fig. 5). According to the angular deviation of the elbow, the push-up motion was divided into the following 3 phases: the first phase was comprised of extension, which corresponded to the ascending Fz; the second phase included when elbow extension was maintained, and corresponded to static Fz, and the third phase included flexion, which corresponded to a descending Fz (Fig. 6). In the palm position, Fx had a larger amplitude than it did in the other hand positions. In the finger position, there were no remarkable findings. In the fist position, a slow Fz onset and low Fy amplitude were registered. By using the push-up device, Fz produced a sharp, straight line in the ascending and descending phases; relatively low amplitude waves of Fy were observed in the ascending

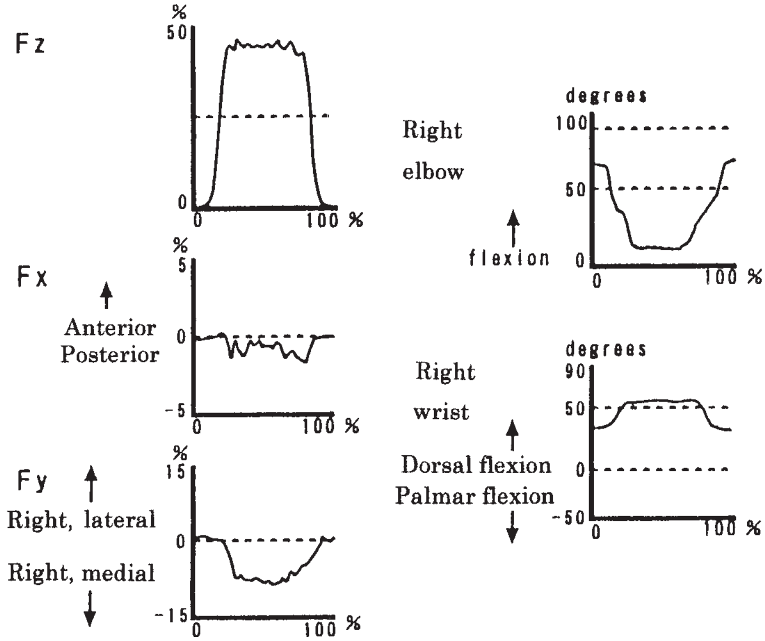

Fig. 4 Hand pressure and angular deviation of the elbow and wrist joints, as measured during push-ups with push-up devices. Fx, Anteroposterior (AP) force (right side); Fy, Mediolateral (ML) force (right side); Fz, Vertical force (right side). Fx, Fy, Fz and angular deviation: horizontal axis indicates the percentage of a push-up cycle.

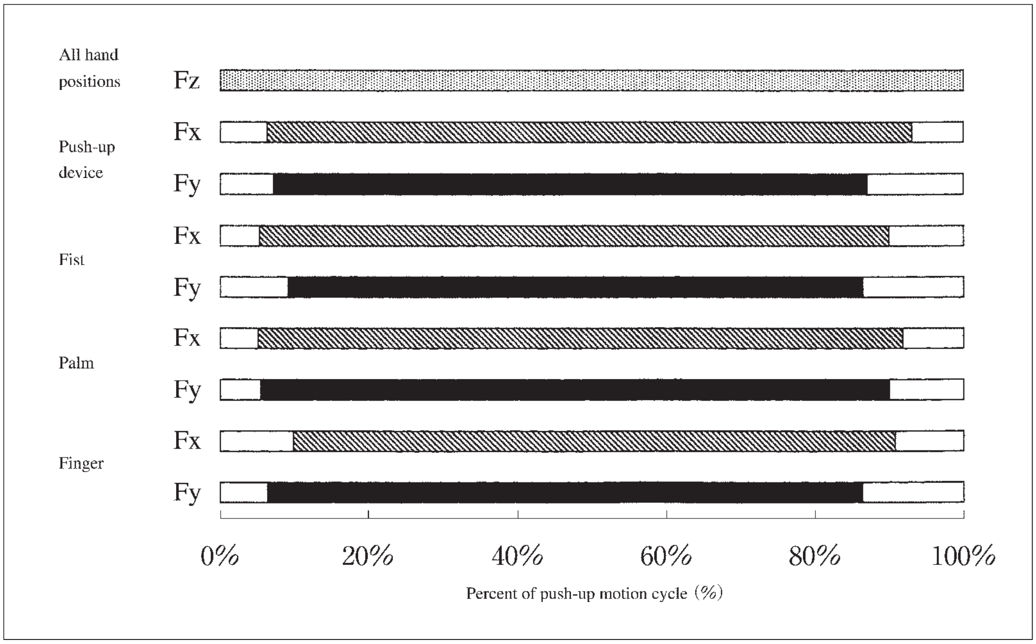

Fig. 5 The starting and ending points of Fx, Fy, and Fz in measured hand positions.

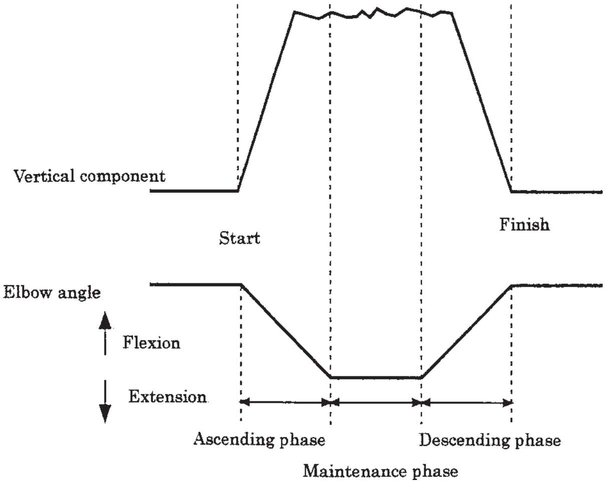

Fig. 6 Fz (vertical component) and angular deviation of the elbow. One cycle consists of 3 phases, *i.e.*, ascending, maintenance, and descending phases.

and descending phases, and low Fx oscillation was observed throughout all of the phases (Fig. 7).

Fx (the AP component) did not show a definite pattern. In the Fx curve, the anterior component and posterior component appeared to alternate. These findings were observed in the case of all 4 push-up techniques.

Fy (the ML component) always showed medial force in the 4 positions. However, the amplitude of the medial component varied depending on the subject's position. The greatest medial component was observed when the subject assumed the palm position, the next greatest was observed with the push-up device, and then with the finger position. The smallest medial component was observed when the subject assumed the fist position.

Fz (vertical force) revealed a trapezoidal shape when the subject assumed the 4 hand positions. A rising curve corresponded with the period when the body was lifted; the upper side of the trapezoid corresponded with the maintenance phase. In addition, the upper side of the trapezoid showed 2 curve patterns, namely, horizontal and convex. Both curves demonstrated a fine zigzag wave. The horizontal line was observed mainly in the patients whose paralysis level was lower than T11. There were no differences among the 4 hand positions curves obtained during the maintenance phase.

As regards angular deviations of the elbow, the angular deviation curve showed almost the same pattern, *i.e.*, a trapezoidal curve. However, a difference in amplitude was observed among the 4 hand positions. The patterns are shown in Table 2.

As regards our study of the angular deviations of the wrist, Table 3 gives the starting angle, direction of motion, maintenance angle, and range of motion.

Discussion

When SCI patients perform a push-up, the body is supported by both arms. Some balancing skills are required in such case in order to control the body's center of gravity. The pressure data recorded by a force plate reflect the body's attempts to balance itself. With such a force plate, Fx represents an AP shift of the center of gravity, Fy represents ML shift, and Fz represents vertical shift.

Ikawa and Tokuhiro [6] reported regularities in starting and disappearing points of each floor reaction

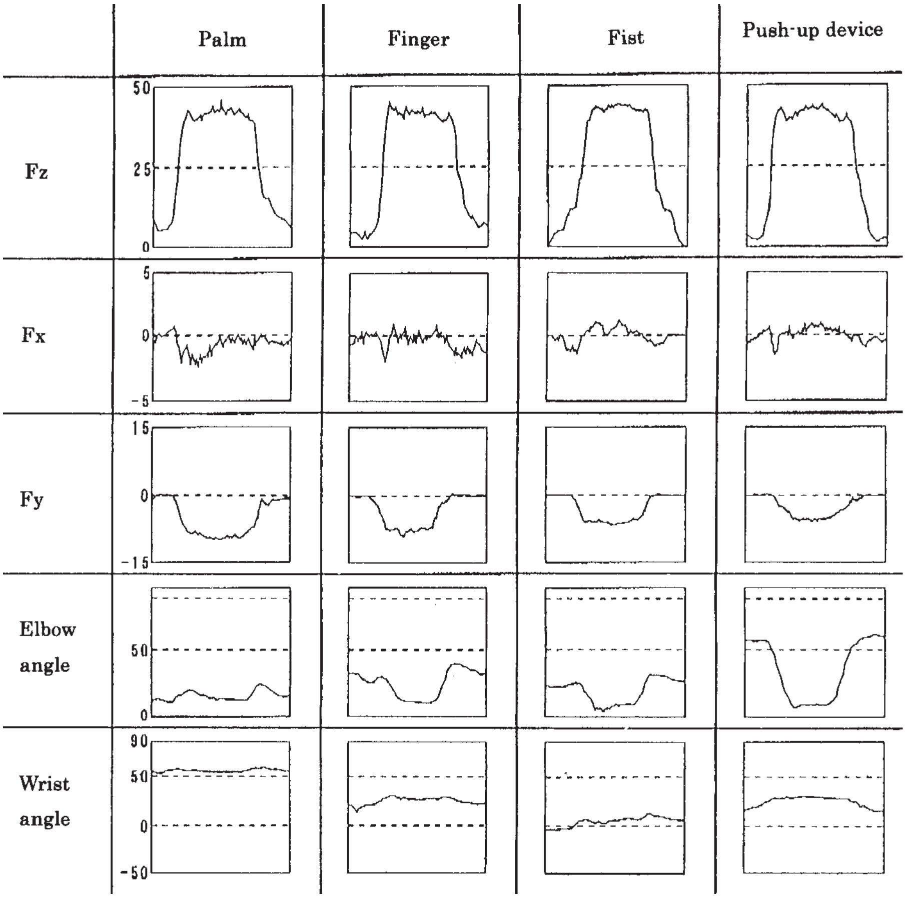

Fig. 7 Typical hand pressure pattern and angular deviation of the elbow and wrist joints during push-ups in the 4 hand positions.

Table 2 The angular deviation of elbows

Elbow angle (degree)	Hand positions			
	Palm	Finger	Fist	Push-up device
Starting angle	23.9	32.9	37.9	69.1
Angle during the maintenance phase	9.4	11.3	16.1	19.9
Range of motion	14.5	21.6	21.8	49.2

Table 3 The angular deviation of the wrists

Elbow angle (degree)	Hand positions			
	Palm	Finger	Fist	Push-up device
Starting angle	64.5	23.7	−6.6	29.6
Angle during the maintenance phase	69.9	28.3	−1.2	40.9
Range of motion	5.4	4.6	5.4	11.3

corresponding to a hand position during push-up exercise in healthy subjects; they concluded that in each case, the required balancing skill was altered by hand position. In our study of SCI patients, we found that the order of forces exerted was not the same in the finger position as in the other positions, *i.e.*, Fz was initiated first, then Fy, followed by Fx (Fig. 5).

Three factors determine the clearance under the buttock gained by push-up movements. The first factor is the extension of the elbows, the second is the downward pull of the scapulas and the third is the anterior rotation of the upper trunk, which involves using the shoulders as fulcrums and supporting the weight of the body on both hands. The first element depends on the power of the triceps brachii, the second depends on the power of the shoulder girdle muscles, in particular, the pectoralis major, serratus anterior, and latissimus dorsi [1, 2, 7]. These muscles are innervated by the C6–C8 nerve roots and in our study were paralyzed in only one of the patients we examined (whose paralysis level was C7). The third factor involved the balancing of the trunk on the upper extremities. The ability to perform such balancing tasks depends on the residual muscle power of the trunk, *i.e.*, on the abdominal muscles and paravertebral muscles. The extent of this residual muscle power depends on the level of paralysis. Patients with high thoracic level paralysis maintain their balance by engaging the unparalyzed muscles in the anterior chest as well as the upper thoracic paravertebral muscles. Such patients keep their spines in the anatomically stable kyphosis position. At the same time, the pelvis tilts posteriorly due to the same mechanisms [8].

In patients with mid-thoracic level paralysis, the upper portions of the paravertebral muscles and the abdominal muscles remain vital; during a push-up, the spinal column displays the normal physiological curve. The balancing of the trunk is easier for these patients, although they expend effort to control the paralyzed regions of their bodies below their pelvis. The patients with lower thoracic or lumbar level paralysis have even more ability to control their spinal column and pelvis. Thus, for these patients, balancing the trunk during a push-up is much easier than it is for the other groups of patients [8].

In the initial stage of the rehabilitation of people with SCI, we employed a push-up device (Fig. 2). To use the device, patients grip the bar with their wrists in the dorsiflexed position, which provides the most kinesiologically stable and powerful grip. Ease of balance is depicted by the lines of Fz, the low amplitude wave of Fy, and the low oscillation of Fx (Fig. 7).

SCI patients often use the palm position to perform normal daily activities such as when they move from a wheelchair to a bed, from a wheelchair to a bathtub, or from a wheelchair to a car. This hand position is stable due to the wide surface area of the palm that offers support. To lift the buttocks higher, patients will place their hands more anteriorly, and will also rotate the upper trunk anteriorly. The large amplitude of Fx in the ascending phase indicates this action (Fig. 7).

The fist position is advantageous in gaining clearance under the buttocks because the distance between the floor and the shoulder is thereby lengthened. However, in this position, the push-up motion becomes unstable, as the weight is supported on the basal phalanges of both fists; thus, the wrist joints are required to be kept in a neutral or slightly palmer flexed position, which is more unstable than both the palm position and the use of a push-up device. To keep the weight-supporting area as wide as possible, the relationship between the floor and the hand must be fixed and the fist must be set adjacent to the body. In this position, the flexors of the wrist and fingers are already tensed to maintain the fist. They therefore have little remaining power to push against the floor, unlike when the subject is in the palm position. This scenario is reflected by the slow onset of Fz in this position. The direction of the push-up in this position appears to be more perpendicular than in the other hand positions. The low amplitude of Fy of this position may also reflect this tendency (Fig. 7).

Not all SCI patients can perform the push-up motion in the spread-finger position. This position requires simultaneous contraction of the wrist and finger flexors and extensors. This position is maintained by the anatomical extension check mechanism and by contraction of the finger and thumb flexors. In this position, the weight bearing surfaces are limited to merely the narrow areas of the fingertips. Therefore, push-ups in the spread-finger position require significant muscle power and balancing ability.

In this study, all subjects with paralysis from levels C7 to T4 were unable to perform push-ups in the finger position. The subject with a neurological level of C7 had muscle weakness in the extensor digitorum communis, extensor pollicis longus, flexor digitorum profundus (FDP) and flexor pollicis longus (FPL). All of the intrinsic muscles in this subject's hands were paralyzed.

The subject with a neurological level of C8 had poor FDP, trace FPL, and paralyzed intrinsic muscles. These levels of injury explain the difficulty of maintaining finger stability in the finger position.

The 3 subjects with T4-level paralysis had sufficiently strong muscles in their hands and forearms. They also had intact nerve roots at sites above T1. Furthermore, their shoulder girdle muscles (pectoralis major, serratus anterior, and latissimus dorsi) were not paralyzed. To support their bodies with their arms, they placed their center of gravity at an initially high level and then moved it anteriorly. This required lateral balancing of the body, especially in the early stage of the ascending phase in the unstable finger position. AP balancing took priority in the other hand positions, which was reflected by the fact that Fy was initiated prior to Fx in the finger position (Fig. 5).

Generally, paralysis of trunk muscles renders the spinal column limp and uncontrollable, regardless of strong arm and shoulder girdle muscles. In patients with levels of paralysis between T1 and T4, we believe that ML balancing may become critical in push-ups performed in the finger position.

The only subjects with long spinal instrumentation (Harrington rods [9, 10] or Luque rod-segmental wire fixation [11]) who could perform push-ups in the finger position had paralysis levels between T5 and T10. No statistical difference was found according to age, body weight, or height between the subjects who could perform push-ups and those who could not. Although there has been some controversy regarding the advantages [12-14] and disadvantages [15-18] of spinal fixation, the present results indicate that spinal instrumentation stiffens the spinal column and aids ML balancing of the paralyzed trunk. Moreover, such instrumentation allows the center of gravity to be lifted higher and then shifted to an anterior position with lateral stability. Based on the fact that all of the subjects with paralysis levels below T11 could perform finger push-ups, we concluded that the muscles above the T11 level play some role in stabilizing the spinal column and preventing lateral shifts of the center of gravity.

Until now, push-up exercises have been studied in 4 hand positions without consideration of neurological level and spinal balancing in the rehabilitation of SCI patients. Here, we conclude that each patient has an appropriate means of performing push-ups, according to his/her level of neurological injury.

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