Table 3
Improvement of MSGS according to maximum walking speed and adductor muscle strength tertiles in intervention group.

Survey variable	Changes compared to baseline[a]	Improvement of MSGS[†] n (%)	Cochran's Q-value	p	Post hoc[‡]
3-Month exercise ($n=8$)					
Maximum walking speed	Increased	3 (37.5)	2.80	0.247	
	No change	4 (50.0)			
	Decreased	1 (12.5)			
Adductor muscle strength	Increased	3 (37.5)	0.50	0.779	
	No change	3 (37.5)			
	Decreased	2 (25.0)			
6-Month follow-up ($n=7$)					
Maximum walking speed	Increased	5 (71.4)	6.50	0.039	In > De
	No change	1 (14.3)			
	Decreased	1 (14.3)			
Adductor muscle strength	Increased	3 (42.8)	0.57	0.713	
	No change	2 (28.6)			
	Decreased	2 (28.6)			

[a] Decreased (De) means lower range (0.0–33.3%), no change (no) means medium range (33.4–66.6%), and increased (In) means upper range (66.7–100%) of tertile.

exercise series at home was 3.8 times per week (23.3% performed everyday, 50.0% 2-3 times per week, 26.7% once or less per week), while the mean exercise time was 29.0 min.

The exercise group showed significant improvement compared with the control group in muscle strength, walking speed and balance. There was a significant group by time interaction for tandem walking ($F=4.70$, $p=0.036$), functional reach ($F=4.18$, $p=0.046$), adductor muscle strength ($F=4.18$, $p=0.045$), usual walking speed ($F=13.03$, $p=0.001$), and maximum walking speed ($F=4.24$, $p=0.044$) with significantly greater increases in the exercise group. The functional decline decreased significantly from 50.0% at baseline to 16.7% after the intervention and follow-up in the exercise group ($Q=16.67$, $p<0.001$), whereas the changes were not significant in the control group. Urinary incontinence was decreased significantly from 66.7% at baseline to 23.3% after the intervention and to 40.0% at the follow-up ($Q=13.56$, $p=0.001$) in the exercise group. However, no significant changes observed in the control group. There were no significant changes concerning fear of falling in either group (Table 2).

Fig. 2 shows the changes in the scores of multiple geriatric syndromes. As shown in Fig. 2, the intervention group showed

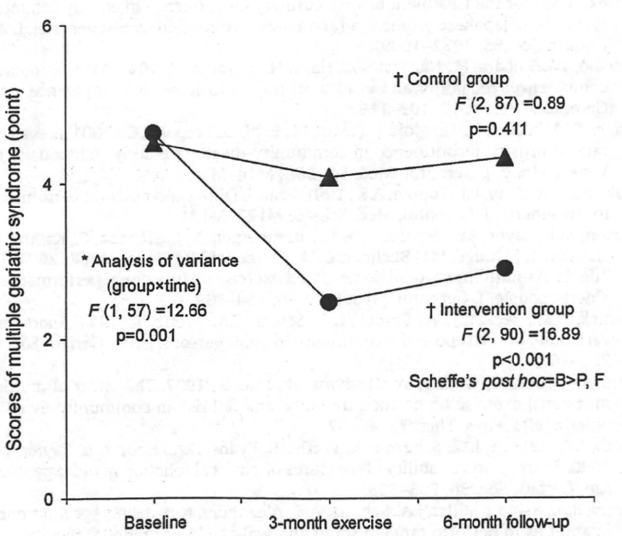

Fig. 2. Change in mean scores of MSGS at baseline, after 3-month exercise, and at 6-month follow-up in intervention (●) and control (▲) group. (*) Comparison of multiple geriatric syndrome scores between intervention and control group. (†) Comparison of within-group multiple geriatric syndrome scores at baseline (B), after the 3-month exercise (P), and at 6-month follow-up (F).

greater and significant decrease compared with the control group ($F=12.66$, $p=0.001$). Within-group scores were compared, and significant changes were observed in intervention group, with the score of multiple geriatric syndromes decreasing significantly after 3-month exercise and at 6-month follow-up ($F=16.89$, $p<0.001$).

Eight subjects after 3-month intervention and seven subjects after 6-month follow-up were improved to normal status of multiple symptoms in the intervention group. Table 3 shows the distribution of the subjects who showed improvement to normal status of multiple symptoms according to the tertiles of maximum walking speed and adductor muscle strength. Within the subjects that showed improvement to normal status of multiple symptoms, a significantly higher proportion had an improved maximum walking speed at the 6-month follow-up ($Q=6.50$, $p=0.039$) compared with those having maintained or decreased walking speed. There was no difference at either time point in the proportion of the improved subjects with increased adductor muscle strength.

4. Discussion

This study demonstrates that the 3-month, multidimensional exercises, consisting of progressive strength training, balance and walking ability exercises along with PFM exercises, improved the usual walking speed, maximum walking speed, abductor muscle strength, tandem walking and functional reach in community-dwelling elderly women with MSGS. Furthermore, the increment of the physical fitness components appeared to contribute greatly to the improvement of the functional decline, urinary incontinence, and multiple symptoms. Therefore, the results of this study suggest that the improvements of the muscle strength, walking speed, and balance, which have been reported as risk factors for geriatric syndromes, may be effective in the improvement of geriatric syndrome.

Several studies of multidimensional intervention trials have reported beneficial effects (Tinetti et al., 1994; Shumway-Cook et al., 1997; Nelson et al., 2004; Gitlin et al., 2006; Kim et al., 2007). In a recent study, Gitlin et al. (2006) conducted a multidimensional home-based intervention in elder adults with functional difficulties, and confirmed that activity of daily living (ADL), instrumental ADL, self-efficacy, fear of falling, and home hazards were all improved and that the effects were sustained even after 6-month. Kim et al. (2007) assessed the effect of PFM and fitness exercises in improving urinary incontinence in elderly community-dwelling Japanese with stress urinary incontinence, and confirmed that decrease in BMI and increase in walking speed may contribute to the treatment of urinary incontinence.

In this study, the prevalence of the functional decline decreased significantly from 50.0% before the intervention to 16.7% after intervention and follow-up. The cure rate of urinary incontinence was 43.3% after the 3-month exercise and 26.7% at 6-month follow-up for the intervention group. On the other hand, no significant improvement was observed in the control group. The effects of this multidimensional exercise affecting only a single symptom of urinary incontinence or functional decline were consistent with previously reported studies. Although the previous studies using multidimensional intervention were targeted to treat only a single geriatric syndrome, the current study was aiming to treat MSGS. Our findings suggest that the multidimensional intervention was significantly effective in the improvement of geriatric syndrome.

We analyzed the relationship between the increment of the physical fitness components and the improvement of the multiple symptoms, despite the small sample size. We found an increment rate of 9.6% in adductor muscle strength after the 3-month exercise and a rate of 12.3% after the follow-up in the intervention group, whereas the changes were not significant for the control group. This difference in the increment rate of muscle strength is not considered to account for the difference in geriatric syndrome improvement rate. However, the proportion of the subjects with improved to normal status of multiple symptoms was significantly higher among those who demonstrated an increase in maximum walking speed at 6-month follow-up ($Q = 6.50$, $p = 0.039$). These results suggest that the increment of walking speed is a major factor for the improvement of the multiple symptoms present in this population. The increased walking ability probably allowed the subjects to increase their physical activity and consequently contributed to the improvement of their functional capacity. But, the current study's results were obtained based on a small sample size. The above relationships need to be further researched in a population study which would contain a larger number of subjects and for a longer follow-up period.

Despite the fact that many studies have reported that exercise is effective in reducing the fear of falling in the elderly (Tennstedt et al., 1998), our intervention had no effect on the fear of falling in both groups. This may be explained by the characteristics of the intervention provided in the present study. Our multidimensional exercises focused on increasing the physical function and did not provide measures such as psychological care. These findings indicate that the comprehensive strategy designed to reduce MSGS in community-dwelling elderly women should include not only exercises addressing to the improvement of the physical functions, but should also incorporate psychological care focusing on reducing the fear of falling.

This study has several limitations. Firstly, the functional decline, urinary incontinence, and fear of falling were assessed using self-reported data obtained through a face-to-face interview, and they were not confirmed by objective and clinical methods. However, several previous studies have indicated that self-reported data have high validity, reliability and objectivity in the analyses of the functional decline, urinary incontinence, and fear of falling (Smith et al., 1990; Howland et al., 1993; Resnick et al., 1994). Therefore, the use of data collected from interviews or self-recording in analyses has minor influence on the interpretation of the results of this study. Secondly, although this study indicates that improvement of physical fitness components such as muscle strength and walking ability contributes to the treatment of geriatric syndrome, it provides no explanation of the mechanism of how increasing functional fitness component improves multiple geriatric symptoms.

5. Conclusions

This study assessed the effects of multidimensional exercises on functional decline, urinary incontinence, and fear of falling in community-dwelling Japanese elderly women with MSGS. The intervention program targeted modification of physical fitness may contribute to a reduction of the functional decline and urinary incontinence, but was not a diminishing symptom over time concerning the fear of falling. Therefore, the intervention strategies designed to reduce MSGS in elderly persons should include not only exercises aiming to the improvement of the physical functions, but should also incorporate psychological care focusing on the reduction of the fear of falling.

Conflict of interest statement

The authors have no conflict of interest to disclose.

Acknowledgment

This study was supported by a Research Grant of the Ministry from Health and Welfare of Japan and a Grant-in-Aid for Scientific Research B (16300226) from the Japan Society for the Promotion of Science.

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Allergology International. 2010;59:53-57
DOI: 10.2332/allergolint.09-OA-0098

ORIGINAL ARTICLE

Pulmonary Function Analysis of Japanese Athletes: Possibly Even More Asthmatics in the Field

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ABSTRACT

Background: The prevalence of bronchial asthma (BA) in youth is increasing in Japan, but very few athletes are reported to be affected with BA. The aim of this study is to analyze pulmonary function test (PFT) in athletes from the aspect of BA retrospectively.

Methods: Medical history questionnaires of 2111 athletes (male: 1549, female: 562) were reviewed. All athletes participated in the institute's athletic test for the first time, from April 2003 through March 2006. Athletes were categorized into three groups; current-BA confirmed and treated by the physician, possible-BA according to the allergic history and/or BA symptoms, and non-BA that is neither of the above two groups. The PFT data were then analyzed.

Results: There were 24 current-BA (1.1%), 137 possible-BA (6.5%), and 183 cases with a past history of BA (PH; 8.7%). Percent of predicted forced expiratory volume in 1 second (%FEV_1) and of predicted peak expiratory flow rate (%PEF) in current-BA (86.2 ± 17.7% and 81.6 ± 19.1%, respectively) and possible-BA (84.7 ± 14.6% and 81.2 ± 17.3%, respectively) were significantly lower than those in non-BA (93.9 ± 13.7% and 93.8 ± 19.8%, respectively), without any significant difference between current-BA and possible-BA. Athletes with PH show impaired obstructive indices; even in non-BA with PH showed lower %FEV_1 (91.3 ± 13.9%, $p < 0.05$) and %PEF (86.8 ± 17.8%, $p < 0.001$) than non-BA without PH (94.0 ± 13.7% and 94.2 ± 19.9%, respectively).

Conclusions: The incidence of BA in Japanese athletes may be higher than currently recognized. More intervention is encouraged for the diagnosis of BA, to avoid any fatal asthma during sports by initiating preventive therapy.

KEY WORDS
asthma, athletic injuries, exercise-induced asthma, exercise-induced bronchospasm, pulmonary function test

INTRODUCTION

A negligible number of Japanese athletes requested the use of an inhaled beta agonist (IBA) at recent Olympic Games[1]; only one out of 268 athletes from Japan applied for permission at the Sydney Games, where 112 out of 594 athletes from the United States of America notified the use. This low prevalence of notification by Japanese athletes may be partly due to the relatively low prevalence of bronchial asthma (BA) patients in Japan.

The prevalence of BA among Japanese children has increased by 3% in the last 20 years, and two recently conducted government surveillances have revealed the rate in school-age children to be 5.7 and 7.6%. In 2003, the Global Initiative for Asthma (GINA) also reported a similar rate of 6.7% as the prevalence of BA symptoms in Japanese school-age children,

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Received 2 March 2009. Accepted for publication 3 July 2009.

Table 1 Medical questionnaire regarding history and symptoms of bronchial asthma and allergy

BA † history:
1. Is the athlete on the follow-up of BA at the clinic? (current-BA)
2. Has the athlete been diagnosed as BA during the childhood? (PH ‡)
BA symptoms:
3. Has the athlete ever been diagnosed as allergic disease other than BA?
4. Has any of the family (siblings or parents) been diagnosed as BA?
5. Does the athlete experience wheezing, chest tightness, breathlessness, cough, or excess of sputum at night or early in the morning?
6. Does the athlete experience wheezing, chest tightness, breathlessness, cough, or excess of sputum after exposure to the certain airborne substances (allergens or pollutants)?
7. Does the athlete experience wheezing, chest tightness, breathlessness, cough, or excess of sputum during and after the exercise?
8. Does the athlete experience wheezing, chest tightness, breathlessness, cough, or excess of sputum as the seasonal exacerbation?
9. Do the athlete' s colds take more than 14 days to clear up? (One point for each "yes" answer to question 3 through 9, and the athlete is considered possible-BA if the score is three or greater.)

† BA, bronchial asthma.
‡ PH, past history of asthma.

which is below the rate for the United States of America, 10.9%.[2]

The prevalence of BA in athletes is higher than in the general population,[3-7] and considering the difference in prevalence between Japan and the United States of America shown above, many Japanese athletes possibly have undiagnosed BA; the percentage of Japanese athletes who applied for the use of IBA is too low referring to the prevalence of BA among Japanese children. Moreover, there is no published report so far, regarding the prevalence of asthma-related disorders among Japanese athletes.

Thus, we have decided to analyze the baseline pulmonary function test (PFT) data regarding the BA background of athletes, since our medical questionnaire for the health check-ups included the BA-related history and symptoms. Recent studies show that the medical questionnaires or interviews are not reliable in identifying the exercise-induced bronchospasm (EIB).[8] EIB should be documented by evaluating the PFT in response to appropriate exercise or provocation tests. However, medical history is still a helpful guide in the clinical diagnosis of BA, and can be used in screening of BA regardless of EIB.

The primary aim of this study was to analyze screening PFT of Japanese athletes from the aspect of BA, by the groups categorized through the scoring of a medical questionnaire regarding asthma symptoms and allergic history.

METHODS

STUDY DESIGN

We conducted a cross-sectional retrospective study of regional elite athletes who participated in their first athletic test performed at the Niigata Institute for Health and Sports Medicine, from April 2003 through March 2006. A total of 2111 athletes (1549 males, 562 females, age 18.0 ± 4.1 years) were included in this study. The data from screening tests were collected during the preparticipation health check-ups, including a medical questionnaire focused on history and symptoms of BA and allergy (Table 1), and baseline PFT. The study procedures including participant's anonymity preservation were approved by the Ethical Committee of the Niigata Institute for Health and Sports Medicine in accordance with the principles embodied in the Declaration of Helsinki, and each subject, parents, or legal guardian provided written informed consent.

ASTHMA AND ALLERGY QUESTIONNAIRE

A detailed BA and allergy history and review of symptoms were obtained using a medical questionnaire as shown in Table 1. The questionnaire consisted of 9 items relevant to the diagnosis of BA, also referring to the medical history consideration shown by GINA,[9] and an athlete was categorized as current-BA, possible-BA, or non-BA. The athlete was considered current-BA if BA was confirmed and treated by the physician, possible-BA if scoring 3 or more items for the allergic history and/or BA symptoms, and non-BA if the athlete was neither current-BA nor possible-BA. Possible-BA, however, was defined as above in this study to categorize athletes into groups, simply for the sake of convenience to analyze baseline PFT retrospectively.

PULMONARY FUNCTION TEST BY SPIROMETRY

A baseline PFT by spirometry was performed for all participants. The best value from three measurements of vital capacity (VC), forced vital capacity (FVC), forced expiratory volume in one second

Table 2 Categorical characteristics of the participants

		Number (%)	Male/Female
Total participants		2111 (100)	1549/562
Current-BA		24 (1.1)	17/7
	(PH+	20	15/5)
Possible-BA		137 (6.5)	97/40
	(PH+	48	40/8)
Non-BA		1950 (92.4)	1435/515
	(PH+	115	80/35)

(FEV_1), peak expiratory flow (PEF) were used and recorded by a spirometer, SpiroSift SP-470 (Fukuda Denshi, Tokyo, Japan.). Predicted values were calculated by the standard formulae originally programmed in the spirometer.

DATA ANALYSIS AND STATISTICS

Percent of predicted FEV_1 (%FEV_1), percent of predicted PEF (%PEF), and FEV_1/FVC (FEV_1%) were analyzed for each category of athletes, current-BA, possible-BA, and non-BA. The data were further analyzed according to the past history of asthma (PH) status. Values for all measurements are expressed as mean (%) ± SD.

Kruskal-Wallis test, and Mann-Whitney *U* tests were used to determine the levels of difference between all groups. Significance was assumed at *p*-values of <0.05.

RESULTS

There were 24 current-BA (1.1%), 137 possible-BA (6.5%), and 1950 non-BA (92.4%) cases. In 183 cases of PH (8.7%), there were 20 current-BA, 47 possible-BA, and 116 non-BA cases. Considering the rate of PH, cumulative morbidity of BA was estimated as 8.9%. The difference between male and female athletes was not discussed in this study, because 562 female athletes were analyzed, and there were only seven cases with current-BA and 40 cases with possible-BA, which resulted in numbers that were too few to see any significance (Table 2).

As shown in Figure 1, current-BA showed a significantly decreased %FEV_1 (current-BA vs. non-BA; 86.2 ± 17.7% vs. 93.9 ± 13.7%), %PEF (81.6 ± 19.1% vs. 94.3 ± 26.2%) and FEV_1% (84.6 ± 8.3% vs. 89.0 ± 5.8%) compared to non-BA, even under the relevant treatment ($p < 0.001$). Interestingly, possible-BA is also significantly decreased in pulmonary function parameters compared to non-BA (possible-BA vs. non-BA; 84.7 ± 14.6% vs. 93.9 ± 13.7% in %FEV_1, 81.2 ± 17.3% vs. 94.3 ± 26.2% in %PEF, and 84.9 ± 7.5% vs. 89.0 ± 5.8% in FEV_1%, all with $p < 0.001$, respectively). However, there was no significant difference between current-BA and possible-BA (Fig. 1). %VC, which is one of restrictive indices in PFT, was of no difference among all groups (data not shown).

To determine the influence of PH on pulmonary function, comparison between groups either with or without PH was performed. Among all participants, the group with PH (PH^+) showed decreased pulmonary function parameters compared to the group without PH (PH^-) (PH^+ vs. PH^-; 89.9 ± 14.3% vs. 93.5 ± 14.0% in %FEV_1, $p < 0.001$. 87.2 ± 17.8% vs. 93.4 ± 20.0% in %PEF, $p < 0.005$. 86.8 ± 6.6% vs. 88.8 ± 6.0% in FEV_1%, $p < 0.001$.). In regard to non-BA, PH^+ also revealed decreased airway function compared to PH^- (PH^+ vs. PH^-; 91.3 ± 13.9% vs. 94.0 ± 13.7% in %FEV_1, $p < 0.05$. 86.8 ± 17.8% vs. 94.2 ± 19.9% in %PEF, $p < 0.001$. 87.3 ± 6.0% vs. 89.1 ± 5.8% in FEV_1%, $p < 0.005$.). In contrast, when the samples are limited to possible-BA, the findings were vice versa; PH^- had decreased airway function in comparison with PH^+ (PH^+ vs. PH^-; 87.6 ± 13.1% vs. 83.2 ± 15.2% in %FEV_1, $p = 0.104$. 89.0 ± 17.6% vs. 77.1 ± 15.7% in %PEF, $p < 0.005$. 86.8 ± 6.8% vs. 84.0 ± 7.7% in FEV_1%, $p < 0.05$.). And even in 24 current-BA, though sample numbers were too small to make conclusions, PH^- in this category had a tendency for decreased airway function compared to PH^+ except for FEV1% (PH^+ vs. PH^-; 87.0 ± 18.5% vs. 81.6 ± 14.4% in %FEV_1. 84.2 ± 19.5% vs. 67.3 ± 10.8% in %PEF. 84.5 ± 8.5% vs. 85.1 ± 7.8% in FEV_1%.) (Table 3).

DISCUSSION

The study by Hammerman, *et al.* showed that there were 5.7% BA or EIB among American high school athletes, and another 6.1% were identified as having undiagnosed BA.[10] In the present study, although the athletes defined as possible-BA were not medically confirmed as BA at the time of visit, the obstructive indices of PFT showed similar results compared with current-BA. These data suggest that a considerable number of these athletes may also have undiagnosed BA.

A recent nation-wide survey on the health and welfare status by the Japanese government revealed that 71.3% of the all-age patients with BA symptoms were under antiasthmatic medication, but only 54.6% of such patients aged between 15 and 34 years were under relevant treatment.[11] Of 161 athletes with either current-BA or possible-PA in our study, less than 15% of them were current-BA who were on medication, thus indicating that the prevalence of untreated BA may also be higher among athletes. Importantly, a 7-year observation of BA deaths by Becker, *et al.* report that of 61 casualties during sport activities, 55 cases had mild intermittent or persistent BA before their fatal attack, and that only 3 of them used long-term controller medication.[12] Although most of the non-current-BA athletes tested in our study had little respiratory symptoms during and after the usual exercise, the undiagnosed BA should thoroughly be detected, in order to avoid any future BA deaths related to exercise and sport activities.

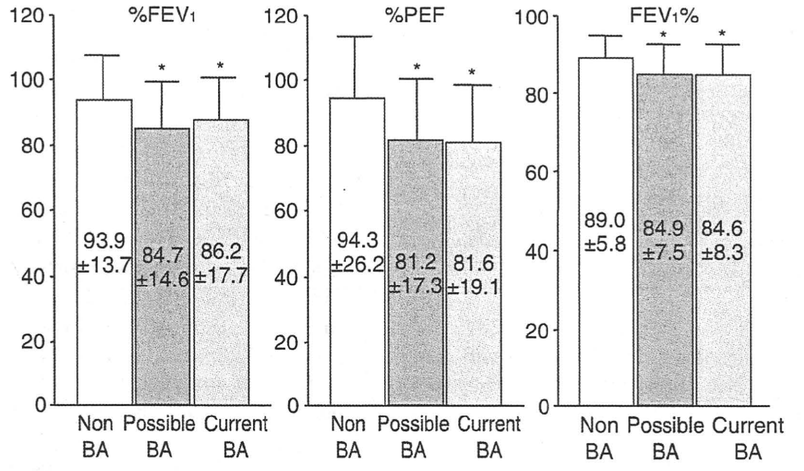

Fig. 1 Obstructive indices of pulmonary function tests (%FEV$_1$, %PEF, and FEV$_1$%) in athletes. Data express mean (%) ± SD. * $p < 0.001$ by the Kruskal-Wallis test.

Table 3 Obstructive indices of pulmonary function test in athletes with or without past history of asthma.

	%FEV$_1$ (%)	%PEF (%)	FEV$_1$% (%)
All participants			
PH^+ (n = 183)	89.9 ± 14.3***	87.2 ± 17.8**	86.8 ± 6.6***
PH^- (n = 1928)	93.5 ± 14.0	93.4 ± 20.0	88.8 ± 6.0
Current-BA			
PH^+ (n = 20)	87.0 ± 18.5†	84.2 ± 19.5†	84.5 ± 8.5†
PH^- (n = 4)	81.6 ± 14.4	67.3 ± 10.8	85.1 ± 7.8
Possible-BA			
PH^+ (n = 48)	87.6 ± 13.1	89.0 ± 17.6**	86.8 ± 6.8*
PH^- (n = 89)	83.2 ± 15.2	77.1 ± 15.7	84.0 ± 7.7
Non-BA			
PH^+ (n = 115)	91.3 ± 13.9*	86.8 ± 17.8***	87.3 ± 6.0**
PH^- (n = 1835)	94.0 ± 13.7	94.2 ± 19.9	89.1 ± 5.8

Data express mean ± SD, *$p < 0.05$, **$p < 0.005$, ***$p < 0.001$; compared with PH^-.
† Insufficient sample numbers for statistical analysis.

Another important message is derived from the results concerning the influence of PH on pulmonary function. The present study has shown that athletes with PH, who were even considered as non-BA, had impaired pulmonary function indices, suggesting they may not have fully recovered from their childhood asthma. In general, it has been reported that up to 70% of BA patients in childhood lose their symptoms during puberty.[13,14] Osward, *et al.* conducted 28-year follow-up study for mild asthmatics in childhood, and suggested that airway obstruction or hyperresponsiveness of the patients would be restored normally even if they did not use inhaled corticosteroids.[15] On the contrary, Agertoft, *et al.* showed that a delay in the introduction of inhaled corticosteroids resulted in incomplete recovery of pulmonary function.[16] Moreover, Pederson, *et al.* reported that early intervention with sufficient doses of inhaled corticosteroids could cure the disease with no recurrence.[17] In this regard, our data may also indicate the possible insufficiency of the treatment approach to childhood BA leading to the symptom takeover through the youth generation, and we should be careful with PH^+ in non-BA patients who have little BA symptoms. Another valuable finding regarding the effect of PH status is that PH^- in possible-BA had decreased airway function compared with PH^+. This tendency is also observed in current-BA (Table 3). Although the details in the treatment history of BA is limited in the medical record, it is more likely that PH^+ in these categories received treatment intervention in the past, which may apparently improve the respiratory function, assuming possible-BA has high potential for being true BA.[18]

We included questionnaires of respiratory symptoms and PFT at baseline medical check-ups, with the belief that these findings are important in the clinical diagnosis of BA. However, they may be insufficient for the diagnosis of EIB. Rundell, *et al.* found that among elite athletes, a diagnosis based on self-reported symptoms is no more accurate than a coin toss. In that study, 61% of EIB-positive athletes reported symptoms, and 45% of normal pulmonary function athletes reported symptoms of EIB.[19] Methacholine challenge test is often used for BA/EIB diagnosis in Japan, but it should be noted that a relatively low sensitivity for EIB diagnosis especially in summer sports is reported for this provocation.[20] We have recently started additional bronchial challenge tests such as eucapnic voluntary hyperpnea and hypertonic saline inhalation, together with exercise challenge which are the current challenge tests also recommended by the International Olympic Committee for the diagnosis of BA/EIB in athletes.

In summary, the PFT results at the Niigata Institute for Health and Sports Medicine were analyzed, according to the historical background of BA, and the prevalence of current-BA, possible-BA, and the cumulative morbidity of BA among the regional elite athletes were 1.1, 6.5, and 8.9%, respectively. A limitation of this study is in the retrospective analysis using a medical questionnaire, of which data had been adopted from sufficient but non-uniform medical record formats. The effectiveness of this medical questionnaire in the uniform medical record format on scoring should be confirmed, and is currently under prospective investigation.

Finally, considering the epidemiological data on BA in athletes available so far, the incidence of BA among the Japanese athletes may be higher than currently recognized. More intervention is encouraged for diagnosing BA and related subtypes to avoid any fatal asthma attacks during sport activities, and to restore originally expected athletic performance of the affected individuals.

ACKNOWLEDGEMENTS

The authors are grateful to Katsutoshi Nishino for expert technical assistance in pulmonary function testing, and to Tetsu Miura for management of the athletic tests.

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J Orthop Sci (2010) 15:64–70
DOI 10.1007/s00776-009-1414-z

JOURNAL OF
ORTHOPAEDIC SCIENCE

Original article

Three-dimensional lower extremity alignment in the weight-bearing standing position in healthy elderly subjects

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Abstract

Background. Although assessment of lower extremity alignment is important for the treatment and evaluation of diseases that present with malalignment of the lower extremity, it has generally been performed using only plain radiographs seen in two dimensions (2D). In addition, there is no consensus regarding the criteria for quantitative three-dimensional (3D) evaluation of the relative angle between the femur and tibia. The purpose of this study was to establish assessment methods and criteria for quantitatively evaluating lower extremity alignment in 3D and to obtain reference data from normal elderly subjects.

Methods. The normal alignment of 82 limbs of 45 healthy elderly subjects (24 women, 21 men; mean age 65 years, range 60–81 years) was analyzed in 3D with regard to flexion, adduction–abduction, and rotational angle of the knee in the weight-bearing, standing position. The obtained computed tomography (CT) and biplanar computed radiography (CR) data were used to define several anatomical axes of the femur and tibia as references.

Results. In the sagittal plane, the mean extension–flexion angle was significantly more recurvatum in women than in men. In the coronal plane, the mean 3D hip-knee-ankle angle was more varus by several degrees in this Japanese series than that in a Caucasian series reported previously. Regarding rotational alignment, the mean angle between the anteroposterior axis of the tibia and the transepicondylar axis of the femur in this series was slightly larger (externally rotated) than that of previously reported Japanese series examined in the supine position.

Conclusions. These data are believed to represent important references for 3D evaluation of morbid lower extremity alignment in the weight-bearing, standing position and are important for biomechanical research (e.g., 3D analyses of knee kinematics) because the relative angles between the femur and tibia are assessed three-dimensionally.

Offprint requests to: T. Sato
Received: January 8, 2009 / Accepted: September 13, 2009

Introduction

Lower extremity alignment is determined by both the spatial relation between the femur and tibia and by the geometry of these bones. Assessment of lower extremity alignment is important when determining and evaluating treatment for diseases that present with abnormal alignment in the lower extremities, such as knee and hip arthritis, patellar dislocation, and congenital malalignment.[1–13] In the field of orthopedic surgery, lower extremity alignment is generally assessed two-dimensionally (2D) on plain radiographs using the hip-knee-ankle angle or the tibiofemoral angle in the coronal plane alone.[11,14,15] However, 2D radiographic measurements are affected by the position of the radiation source and the orientation of the subject's pelvis and lower extremities.[16] Therefore, the accuracy and reproducibility of this method are insufficient for detailed investigations. In addition, rotational alignment cannot be assessed on plain radiographs.

Despite remarkable recent developments in medical imaging technologies that enable visualization of the three-dimensional (3D) geometry of bone and alignment of the lower extremity, few studies have reported quantitative 3D evaluations of lower extremity alignment in the weight-bearing, standing position using 3D digital bone models. In addition, there remains a lack of consensus regarding the criteria for quantitative 3D assessment.

As previously reported, we developed a method for assessing 3D lower extremity alignment in the standing position using 3D digital bone models; this system has been in clinical use since 2002.[17,18] To evaluate morbid alignment in the lower extremities of patients with hip and knee arthritis and other diseases, it is vital to obtain normal data of lower extremity alignment from healthy subjects as a reference. One of the purposes of this study was to obtain these reference data by quantitative, 3D evaluation of lower extremity alignment in healthy elderly subjects so we could compare them with data from osteoarthritis patients' alignment, thereby increasing our knowledge of the clinical state of the disease in future research. Another purpose was to establish the criteria for these evaluations.

Materials and methods

This study was performed according to the protocol approved by the investigational review board of our hospital and Niigata University. All subjects gave informed consent to participate in this study.

Subjects

We assessed 82 limbs of 45 healthy elderly subjects (24 women, 21 men; 37 bilateral and 8 unilateral) who had no pain, history of trauma, knee injury, knee complaints, or radiographic abnormality in the lower limb; they also had no osteoarthritis or rheumatoid arthritis. Unilateral data had been previously collected for another study, and the subjects' opposite lower limbs did not have any of the above-mentioned disorders. The average age of the subjects was 65 years (range 60–81 years).

Three-dimensional digital bone models

Computed tomography (CT) scans with a 2-mm interval were obtained of the femur and tibia of each subject. A 3D digital model of each femur and tibia was reconstructed from the CT data using 3D visualization and modeling software (Zedview; LEXI, Tokyo, Japan) and displayed as a point group. The anatomical coordinate systems were established using 3D model digitizing software (Model Viewer; LEXI) according to the method of Sato et al.[17,18] (Fig. 1). Several anatomical reference points (described below) were digitized, and the reference axes used in the present study were then installed.

Three-dimensional image-matching procedure

Biplanar computed radiography (CR) images of the subjects' lower extremities were obtained in the weight-bearing, standing position with the knee fully extended and toes in the neutral position using the 3D lower-extremity alignment assessment system previously reported.[17–19] These images were downloaded to a personal computer. Using the camera calibration technique,[17] we projected the cited 3D digital bone models onto the biplanar CR images by matching the silhouettes of the digital models to the contours of the respective CR bone images via 3D rotation and translation.

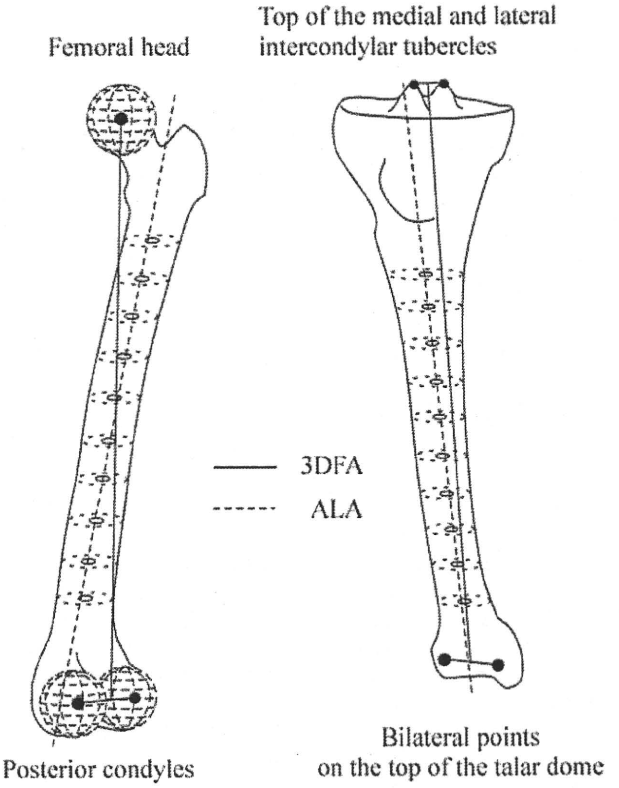

Fig. 1. Bony reference points and anatomical axes defined on the femur and tibia. *Continuous lines*, three-dimensional functional axes (*3DFA*) [11]; *dotted lines*, anatomical longitudinal axes (*ALA*)

After these image-matching procedures, a 3D view of the digital bone model that accurately reproduced the spatial relation between the femur and the tibia at the time of CR projection was displayed; and all alignment parameters (described below) were automatically calculated. The maximum spatial errors of this procedure were 0.5 mm when determining distance and 0.8° when determining orientation.[17] The maximum errors in the proposed image matching procedure for determining the relative pose and position between the femur and tibia were 1.6 mm distance and 1.5° orientation.[19] With regard to the reproducibility of the calculated angles, the maximum interobserver error, including all processes of the analysis, was 1.9°, and the maximum intraobserver error was 0.8°.

Definitions of anatomical parameters

Anatomical axes

For true 3D evaluation of lower extremity alignment, the anatomical reference axes themselves must also be defined in 3D. To define the anatomical longitudinal axes of the femur (ALA-f) and tibia (ALA-t) in 3D, a

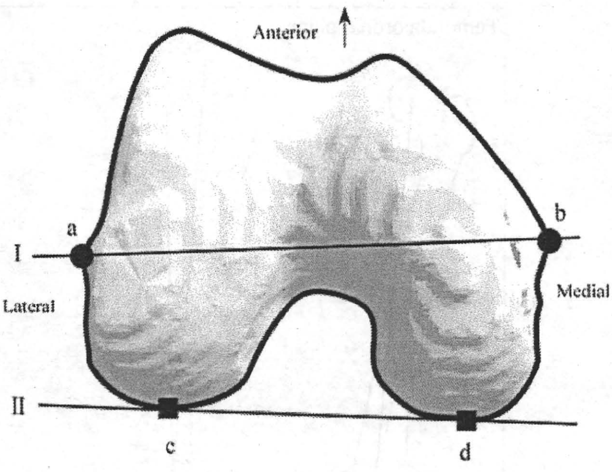

Fig. 2. View of the distal femur. *a*, *b*, prominences of the medial and lateral femoral epicondyles; *c*, *d*, posterior-most points of the medial and lateral femoral condyles; *I*, clinical transepicondylar axis (CTEA); *II*, femoral posterior condylar axis (PCA-f)

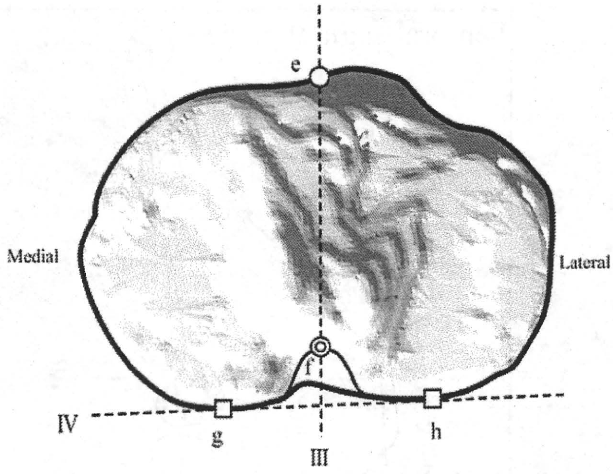

Fig. 3. View of the proximal tibia. *e*, medial edge of tibial tubercle; *f*, anterior-most point of insertion of the posterior cruciate ligament; *g*, *h*, posterior-most points of medial and lateral condyles. *III*, anteroposterior axis of the tibia (APA-t); *IV*, tibial posterior condylar axis (PCA-t)

point group centroid was calculated automatically for the 10 respective cross-sectional planes that divide the diaphysis into 11 equal sections. The ALA was defined as a regression line obtained from approximating distances from these 10 centroids by the least square method (Fig. 1). The 3D functional axes of the femur (3DFA-f) and tibia (3DFA-t) were defined according to the method proposed by Sato et al.[18] 3DFA-f was defined as a line connecting the center of the femoral head and the midpoint of the spheres that represent the medial and lateral posterior femoral condyles. 3DFA-t was defined as a line connecting the midpoint of the eminences of the medial and lateral tibial spines and the center of the ankle joint. Additional axes were defined to assess rotational alignment. For the femur, the posterior condylar axis (PCA-f) [20,21] was defined as a line connecting the posterior-most points of the medial and lateral femoral condyles; and the clinical transepicondylar axis (CTEA) [22,23] was defined as a line connecting the prominences of the medial and lateral epicondyles (Fig. 2). For the tibia, the posterior condylar axis (PCA-t) [24] was defined as a line connecting the posterior-most points of the medial and lateral tibial condyles. The anteroposterior axis of the tibia (APA-t)[25] was defined as a line connecting the anterior-most point of the tibial insertion of the posterior cruciate ligament (PCL) and the medial edge of the tibial tubercle[26] projected onto the axial plane of the tibial coordinate system (Fig. 3).

Extension–flexion angle

The anatomical extension–flexion angle of the knee was defined in two ways: (1) as the angle between ALA-f and ALA-t projected onto the sagittal plane of the femoral coordinate system, termed the 3D anatomical flexion angle (3DAFA); and (2) as the angle between 3DFA-f and 3DFA-t projected onto the same plane, termed the 3D mechanical flexion angle (3DMFA) (Fig. 4). We believe that these angles are each alternative for conventional parameters for evaluating limb alignment: 3DAFA is the 3D version of the definition of knee flexion angle, which is generally utilized for clinical examination; and 3DMFA is the 3D and sagittal version of the conventional hip-knee-ankle angle (HKA).

Adduction–abduction angle

The adduction–abduction angle was also defined in two ways: (1) as the angle between ALA-f and ALA-t projected onto the femoral coronal plane, termed the 3D tibiofemoral angle (3DTFA); and (2) as the angle between 3DFA-f and 3DFA-t projected onto the same plane, termed the 3D hip-knee-ankle angle (3DHKA) (Fig. 5). These two angles are literally 3D versions of TFA and HKA, respectively.

Rotational angle

The relative rotational angle between the femur and tibia at the knee joint was defined in two ways: (1) as the angle between PCA-f and PCA-t projected onto the axial plane of the femoral coordinate system, termed the posterior rotational angle (PRA); and (2) as the angle between CTEA and APA-t projected onto the same plane, termed the functional rotational angle (FRA). We defined PRA as a stable angle for accurate assessment, such as motion analysis. FRA was defined particularly for considering the target alignment of the implants of total knee arthroplasty (Fig. 6).

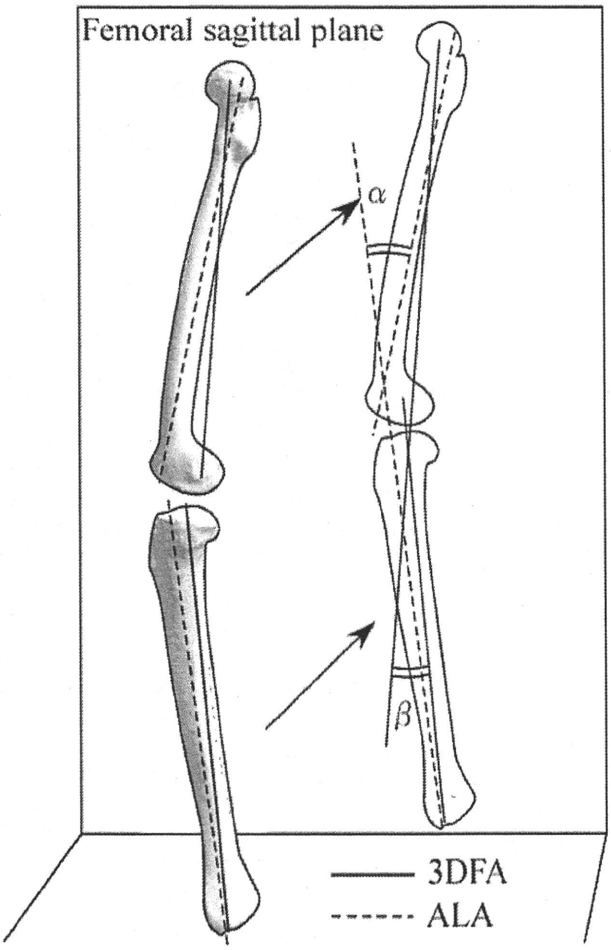

Fig. 4. Reference axes projected onto the femoral sagittal plane. α, 3D anatomical flexion angle (3DAFA), defined as the angle between the ALA-f and ALA-t; β, 3D mechanical flexion angle (3DMFA), defined as the angle between 3DFA-f and 3DFA-t

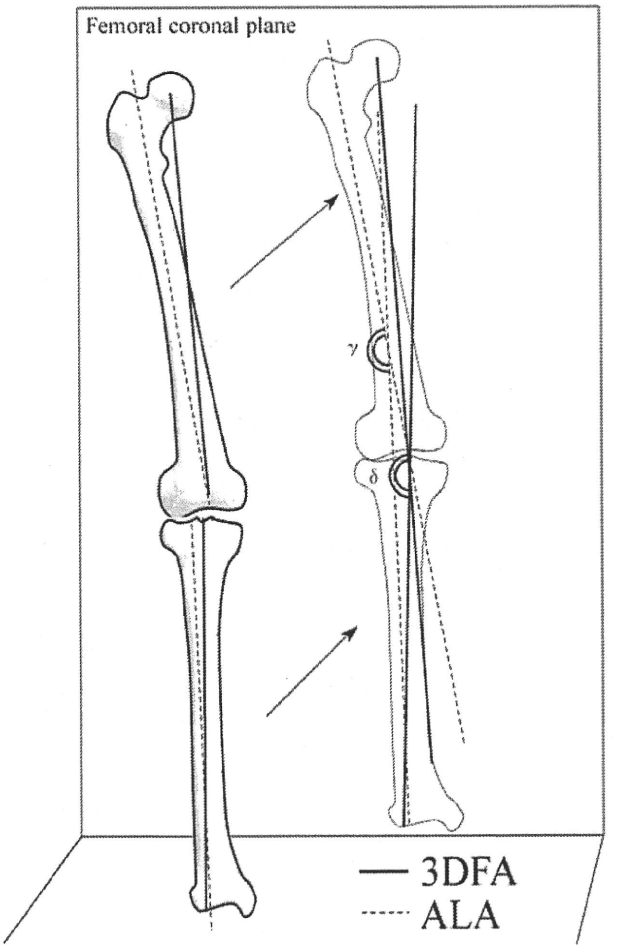

Fig. 5. Reference axes projected onto the femoral coronal plane. γ, 3D tibiofemoral angle (3DTFA), defined as the angle between the ALA-f and ALA-t; δ, 3D hip-knee-ankle angle (3DHKA), defined as the angle between the 3DFA-f and 3DFA-t

Statistical analyses

Differences in all of the angles for sex were assessed using Student's *t*-test, with the level of significance set at $P < 0.05$. The associations between each plane were investigated using regression analysis.

Results

The mean value and standard deviation of each parameter are described in Table 1. Both of the extension–flexion angles (3DMFA and 3DAFA) were significantly ($P = 0.03$) lower (genu recurvatum) in women than in men; in contrast, no difference was found for adduction–abduction or rotational angles with regard to sex. There were no significant correlations between any combinations of three planes with either of the total or by sex. Although all the angles demonstrated near-normal distributions, wide variations were shown for all angles.

Discussion

We conducted a 3D assessment of alignment of the lower extremities in healthy subjects in weight-bearing, standing position using an anatomical coordinate system established by various bony landmarks on 3D digital bone models. The use of 3D digital models reconstructed from CT data enabled accurate assessment of several clinically important bony landmarks, including the femoral epicondyles and insertion of the posterior cru-

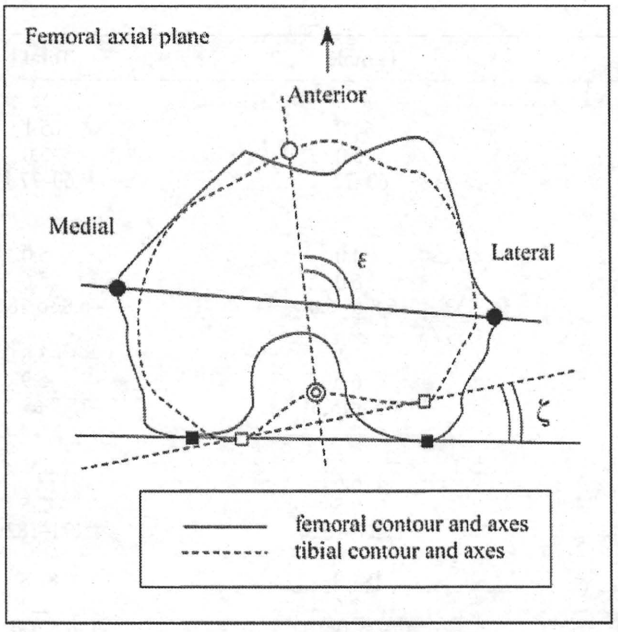

Fig. 6. Reference axes projected onto the femoral axial plane. ε, functional rotational angle (FRA), defined as the angle between the PCA-f and PCA-t; ζ, posterior rotational angle (PRA), defined as the angle between the CTEA and APA-t

ciate ligament (PCL), which are particularly useful for evaluating rotational alignment between the femur and tibia. Cooke et al.[14] also reported a 3D evaluation of lower extremity alignment in the standing position using a similarly calibrated frame but without utilizing the 3D geometry of bone; thus, the important landmarks described above could not be evaluated and accurate evaluation of rotational alignment could not be achieved. Taking into account that recent remarkable development in CT and magnetic resonance imaging (MRI) technology enables accurate 3D information of bone geometry to be obtained relatively easily, we think that it is reasonable to use this 3D information for precise evaluations of lower extremity alignment.

Regarding the definitions of the parameters for alignment evaluations, all angles that describe a relative angle between the femur and tibia were projected onto respective planes of the femoral coördinate system in the present study. Although it was a relatively complicated procedure, we believe that all angles should be projected onto the planes of any anatomical coordinate system of the subject's own bone, and that it was the only way to eliminate the measuring errors caused by the postures of the subjects and the positions of the radiation sources used for conventional 2D evaluation by plain radiography.[16]

Although we found no previous studies that reported evaluation of lower extremity alignment using the same 3D concept as that proposed in the present study, several authors have reported their findings of entire lower extremity alignment in each plane, as follows. With regard to sagittal alignment, Minoda et al. were the first to report a 2D evaluation[10] of healthy subjects in the standing weight-bearing position; they used lateral plain radiography, which revealed a knee flexion angle of 0.8° ± 4.2° (range –6.2° to 9.2°). Compared with the results of their study, the mean 3DMFA in the present study is slightly more recurvatum, probably reflecting differences in the definitions of the reference axes in the two studies: In the present study, all reference axes were defined three-dimensionally, whereas in Minoda's study they were defined two-dimensionally. Another factor possibly reflecting the difference in the results between the two studies was that they used the fibula as the lower limb axis, whereas we used the tibia (ALA-t). With regard to differences between the sexes, our results found significantly more extension (genu recurvatum) in women, as reported by Nguyen and Shultz.[27] We believe that the results of the present study regarding the knee extension–flexion angle (e.g., 3DAFA and 3DMFA) may be used as reference data when evaluating the knee flexion angle anatomically in such situations as knee motion analysis or accurate clinical assessment of range of motion.

Regarding coronal alignment, Moreland et al. reported that the mean knee adduction–abduction angle measured on plain long-leg anteroposterior radiography was 178.5° for the right and 178.9° for the left.[11] Cooke et al. also reported coronal alignment of the lower extremity as the HKA angle in healthy subjects in the standing position[14] and described almost the same alignment as that reported by Moreland et al. Compared with these studies, the mean adduction–abduction angle (3DHKA) in the present study was slightly greater (genu varum). The results of coronal alignment (3DHKA and 3DTFA) in the present study were almost the same as the results of two previous studies[13,28] that reported coronal alignment of lower extremities in Asian populations. Therefore, we believe that the difference in coronal alignment between the results of our series and that of Moreland et al.'s study reflected a racial difference, rather than a difference in the methodologies.

Akagi et al.[26] measured the rotation angle of the knee joint in healthy subjects in the supine position, reporting a value of 0° ± 2.8° (range –6.3° to 5.2°). Compared with this previous study, the results of the present study show slightly greater external rotation of the tibia against the femur, probably reflecting differences in the definitions of the reference axis of the femur and in the subjects' posture in the two studies. In the Akagi et al. study, the surgical transepicondylar axis[26] (SEA) — defined as the line connecting the sulcus of the medial epicondyle and

Table 1. Angles: means, standard deviations, and ranges

Parameter	Male	Female	Total
Age			
Mean	65.6	64.8	65.1
SD	5.0	5.0	5.0
Range	60–74	60–77	60–77
Extension–flexion angle (°)			
3DAFA			
Mean	6.1	4.0	5.0
SD	5.1	6.0	5.6
Range	–6.5 to 5.1	–6.8 to 6.0	–6.8 to 18.3
3DMFA			
Mean	–2.2	–5.1	–3.8
SD	5.3	6.0	5.9
Range	–15.7 to 5.3	–15.5 to 6	–15.7 to 9.7
Adduction–abduction angle (°)			
3DTFA			
Mean	177.5	176.6	177
SD	2.5	2.5	2.5
Range	172.1–182	171.7–182	171–182
3DHKA			
Mean	181.8	181.8	181.8
SD	2.2	2.6	2.4
Range	177.8–186.5	176.6–188.4	176.6–188.4
Rotation angle (°)			
PRA			
Mean	–1.4	–2.6	–2.1
SD	6.9	6.4	6.6
Range	–14.1 to 12.1	–14.8 to 14.3	–14.8 to 14.3
FRA			
Mean	87.3	84.4	85.7
SD	4.5	6.0	5.1
Range	70.5–104	62.5–99.1	64.9–106.0

AFA, anatomical flexion axis; MFA, mechanical flexion axis; TFA, tibiofemoral angle; HKA, hip-knee-ankle angle; PRA, posterior rotation angle; FRA, functional rotation angle

the lateral epicondyle — was utilized, whereas the CTEA was utilized in the present study because the sulcus of the medial epicondyle was sometimes not present.[29] With regard to the subject's posture, the present study is the first in which the relative rotational angle between the femur and tibia was assessed in the weight-bearing, standing position with the knee fully extended; this angle was assessed in the supine position in the previous studies. Therefore, we believe that the tibia was more externally rotated against the femur in this position than in the supine position, achieving "screw-home movement" during terminal extension of the knee.[30]

Throughout the results, the present study shows marked variability among individuals, and there was no clear correlation between each plane. These facts suggest the difficulty of anticipating entire limb alignment from one parameter in any plane. Assessment of each parameter is thought to be required for detail inspections.

There were several limitations in this study. First, the number of subjects was relatively small because it was difficulty finding a large number of volunteers of the required age who were healthy and who were willing to undergo a CT scan of the entire lower extremity. A larger number of subjects is considered necessary to provide more reliable reference data. Second, the radiation dose delivered during this procedure was higher than that for a plain radiograph because CT scanning was used. New methods for producing 3D digital bone models from images taken by other radiation-free devices, such as MRI, are currently under development. Finally, the definition of "healthy" subjects in this study was based on our subjective determinations. It is possible that subjects who did not have any pain or disease in the lower extremity during the period of this research may develop disease later. Elderly subjects were investigated in this study because we thought that the above possibility would be reduced if the ages of the subjects were relatively high.

In the present study, normal alignment of the lower extremities was analyzed in three dimensions in the weight-bearing, standing position using several anatomical axes defined three-dimensionally. We also suggested definitions of anatomical extension–flexion, adduction–abduction, and rotational angle of the knee, which were then measured three-dimensionally in healthy subjects. These data are believed to represent important references for determining the above angles in 3D knee motion analysis and in other accurate evaluations regarding 3D knee alignment.

Acknowledgments. The authors thank the staff of the Department of Radiology at Niigata Rinko Hospital for their assistance.

The authors did not receive and will not receive any benefits or funding from any commercial party related directly or indirectly to the subject of this article.

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関節鏡視下手術支援システムを用いた大腿骨孔位置の決定

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Determination of the femoral tunnel placement using a navigation system for arthroscopic surgery.

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Abstract

We developed a navigation system for arthroscopic surgery so that operators could intuitively understand preoperative planning during surgery. In order to establish such a system, we have been developing a system of superimposing 3D bone-models reconstructed from preoperative tomographic images upon the arthroscopic image on a real-time basis. Such superimposition facilitates visualization of surgical planning using the intraoperative arthroscopic image if it is incorporated into the bone model before surgery. The present study evaluated the overall accuracy of the superimposing system using a cadaveric knee. For accuracy verification, we placed a target point in the femoral tunnel for anterior cruciate ligament reconstruction. In experiments, a metal pin was used as the target point. The position of the pin superimposed upon arthroscopic image of the joint filled with saline was measured by using a measuring probe. Experiments showed that the error of the target evaluated as the distance between the actual point and the measured point was 1.95 mm on average, suggesting that our system has the potential to be applied to the navigation for arthroscopic surgery. Future challenges are to improve the overall accuracy and to introduce MRI models of the cartilage into the system.

Key words : arthroscopic surgery, computer-assisted orthopaedic surgery, accuracy verification, cadaveric experiment.

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はじめに

関節鏡視下手術は，低侵襲であり近年多くの手術に応用されている．しかし，カメラの視野範囲が狭い，カメラ辺縁部の歪みが大きいなどの制約があるため，術者には高い技術習熟度が要求される．そのため現在，術中に術者を支援するシステムが強く求められている．しかし，近年発展しているナビゲーション技術は，鏡視下手術の分野にはいまだ普及していない．そこで我々は「術者が感覚的に理解しやすい関節鏡視下手術ナビゲーション」をコンセプトとして，術中の鏡視画像に術前計画を可視化するシステムを開発してきた[2),5),6)]．

先行研究では，切断肢を用いて実際の術場に近い環境を設定し，その中でシステムの精度を実験的に評価した[2)]．今回は，膝前十字靭帯（ACL）再建術における大腿骨孔位置を目標点に設定し，切断肢を用いてシステムの総合精度を評価した．

システム構成

1．システム概要

本システムは，30°斜視鏡（Smith&Nephew社，Germany），LCDモニタ，プローブ，トラッキング装置（ProReflex MCU240，Qualisys社，Sweden），コンピュータ（LATITUDE D620，DELL社，USA），オーバーレイ表示機能付ダウンコンバータ（Tempest SX PC VIDEO OVERLAY，ADTECHNO社，東京）からなる（図１）．関節鏡・大腿骨・プローブには，トラッキング用のマーカをそれぞれ４個固定した．事前にコンピュータに与えるデータは，関節鏡の内部・外部変数，３次元骨モデル，マーカ座標系に対する３次元骨モデルの位置・姿勢（図４），マーカ間距離である．術中における関節鏡・大腿骨・プローブの位置関係は，マーカ・トラッキングによりリアルタイム計測する．位置の計測誤差は，予備実験より0.71±0.09mmであった．カメラ台数は２台とし，マーカの識別にはマーカ間距離を用いた．図１に示すように，骨マーカ位置から骨モデルの実空間における位置・姿勢を推定し，それを関節鏡に仮想投影すれば，骨モデルの仮想鏡視画像を得ること

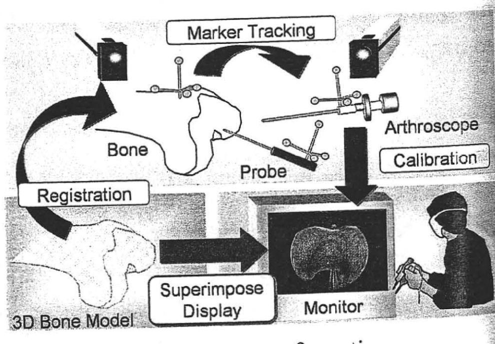

図１．System configuration.

ができる．それを実際の鏡視画像にオーバーレイ表示する（図2）．

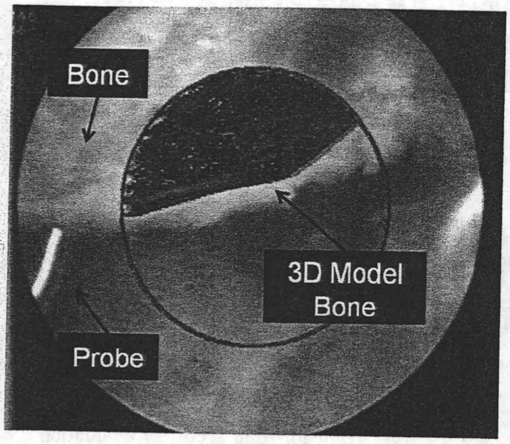

図2．Superimpose display in which a computer model of the bone was superimposed over the actual bone surface on a real-time basis.

2．関節鏡カメラ校正

カメラ校正では，関節鏡の内部変数（焦点距離，画像の歪み）と外部変数（ワールド座標系に対するカメラの位置・姿勢）を求める必要がある．我々は，関節鏡先端と校正ボード間を水で満たした校正装置を製作した（図3）．校正ボードには，直径1mmの鋼球マーカを3mm間隔で7×7個配置した．校正用の3次元点列は7×7×6点とし，それらは，精密移動ステージでボードを面に垂直な方向に5mm間隔で25mm並進移動して作成した．ワールド座標系は，移動ステージ上に設定し，それに対する鋼球マーカの座標を三次元座標測定器（FALCIO-Apex707，MITUTOYO社，神奈川）で測定した．3次元点列を関節鏡で撮影し，その鏡視画像をDVカメラ（DCR-TRV20，SONY社，東京）を介してコンピュータに取り込んだ．次に画像中で鋼球マーカを手動ディジタイズし，画像座標系における2次元座標を求めた．内部・外部変数の推定には，中村らのカメラ校正法[7]を用いた．校正誤差（面内での2次元距離）は平均0.09±0.003mmであった．

3．3次元骨モデルの作成と座標系の設定

3次元骨モデルは，CT撮像データから専用ソフトウェアZed View（LEXI社，東京）を用いて作成した．撮影装置はSENSATION16（SIEMENS社，Germany）を使用し，スライス間隔は1.0mmとした．

骨モデルの解剖学的座標系Σ_{Ana}は，我々が従

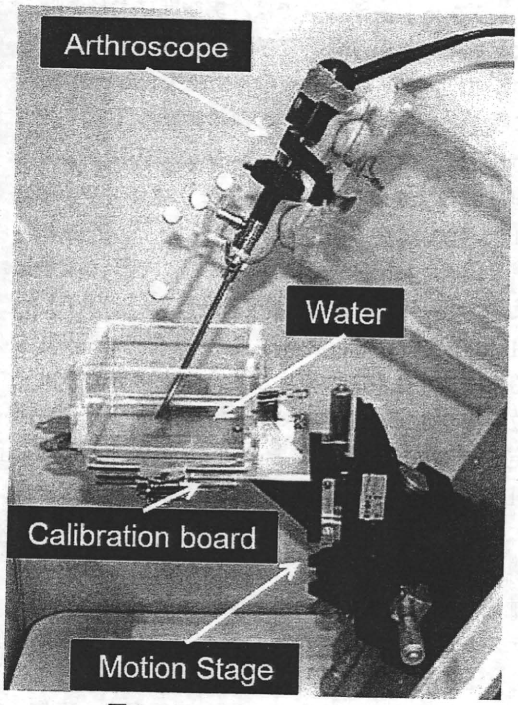

図3．Camera calibration unit.

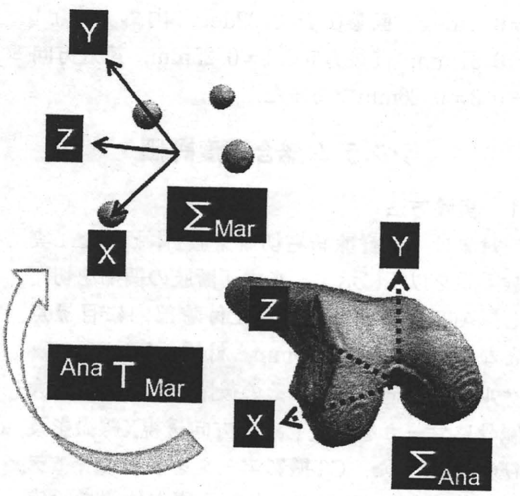

図4．3D-bone model and coordinate systems : ${}^{Ana}T_{Mar}$ denotes the coordinate transform for Σ_{Ana} to Σ_{Mar}.

来から用いてきた座標系[3]にできるだけ近くなるように任意に設定した（図４）．座標系の設定には，専用ソフトウェアModel Viewer（LEXI社，東京）を用いた．

４．レジストレーション

レジストレーションでは，実空間における３次元骨モデルの位置・姿勢を推定する．そのためには，前述のΣ_{Ana}から骨に設置したマーカ上に設定した座標系Σ_{Mar}への座標変換${}^{Ana}T_{Mar}$を求めればよい．レジストレーション手法は，２方向透視X線画像と３次元骨モデルを用いた2D/3Dレジストレーションとした．

レジストレーション手順を以下に示す．まず骨及びマーカを２方向透視X線撮影（ARTIS dTA, SIEMENS社，Germany）し，撮影時を再現する仮想空間を設定する．次に，マーカの３次元位置を２つの透視画像から推定し，Σ_{Mar}を設定する．仮想空間に骨モデルを呼び込み，2D/3Dレジストレーションを用いて透視X線像に骨モデルの仮想投影像を重ね合わせる[1]．透視X線画像の骨輪郭は，半自動抽出法を用いて抽出した[4]．その結果，仮想空間における骨モデルの位置・姿勢が得られる．これらの手順から，Σ_{Ana}からΣ_{Mar}への座標変換${}^{Ana}T_{Mar}$が得られる．（図４）．レジストレーション誤差は，予備実験より屈曲伸展0.1±0.11deg，内反外反0.1±0.24deg，回旋0.4±0.32deg，内外方向0.1±0.51mm，前後方向0.1±0.25mm，遠近方向−0.3±0.26mmであった．

システム総合精度評価

１．実験方法

対象は，新鮮凍結右切断下肢1体とした．実験手順を以下に示す．まず切断肢の関節を切開し，ACLを切除した．ACL付着部内に目標点となるピン（径：0.89mm，材質：チタン・ニッケル合金）を刺入し，その後閉創した．次に大腿骨にマーカを設置し，２方向透視X線撮影及びCT撮影した．CT撮影データを用いて骨モデルを作成し，CTモデル上の目標点位置を設定した（図５）．この３次元値を精度評価の「真値」とした．最後に鏡視画像上に目標点を表示し，表示された目標点をプローブでディジタイズした（図６）．この３次元値を「測定値」とした．誤差は「真値と測定値との距離」とした．検者は整形外科医３名とし，ディジタイズ回数は７回とした．

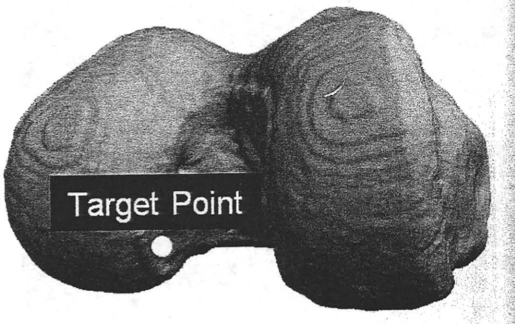

図５．Target point for total accuracy evaluation.

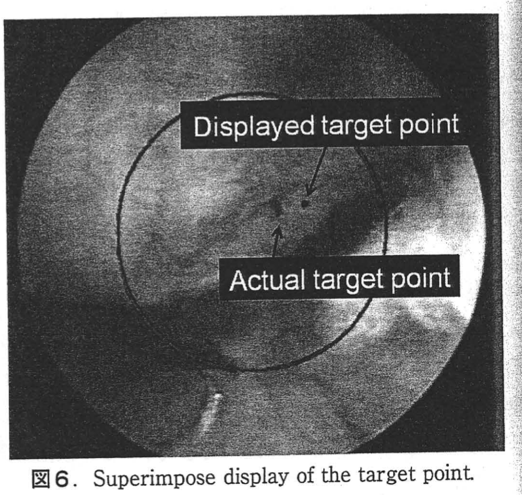

図６．Superimpose display of the target point.

２．実験結果

図７にシステム総合精度評価の結果を示す．誤差は検者Aで2.01±0.067mm，検者Bで1.94±0.117mm，検者Cで1.90±0.147mmであった．

考　　察

我々は関節鏡視下手術の支援を目的として，骨モデルを術中の鏡視画像に重ね合わせて表示するシステムを開発してきた[2),5),6)]．今回はACL再建術における大腿骨孔位置を目標点に設定し，システムの総合精度を評価した．本システムの特徴は，術前計画を鏡視画像上にリア

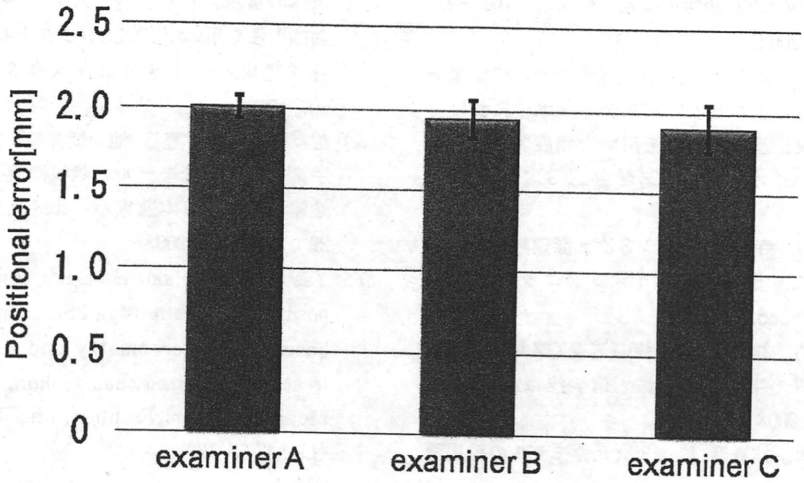

図７．Positional error of the target point : the error was evaluated as the distance between their actual position and corresponding measured position.

ルタイムで表示できることであり，過去に同様のシステムは開発されていない．実験よりACL再建術において術前に決定した大腿骨孔の位置を術中の鏡視画像に直接表示可能であり，術者にとって理解しやすい手術ナビゲーションシステムであると考えられる．さらに手術支援だけでなく，次に述べるように，関節鏡視下手術において様々な定量評価が可能になると考えられる．

３次元モデルを用いれば，局所の解剖などを反映した術前計画が可能となる．その計画結果，例えば骨孔の位置・姿勢などは，臨床で一般的に用いられるX線やCTなどの医療画像情報を用いて，多様に提示できる．例えば，関節鏡画像上に骨モデルと術前計画情報を同時に表示できるため，手術中にいくつもの画面でデータや状況を確認する必要がなくなる．関節鏡画像内での術者の判断は，経験や主観的な判断に依存しやすい．しかし，本システムを用いれば，術前計画や術後での定量評価が可能になり，さらに術式間あるいは術者間の客観的比較も可能になる．このように，本システムは関節鏡視下手術ナビゲーションに応用できる可能性が高いと考えられる．

システム総合精度は，検者３名の平均誤差で1.95mmであった．この結果は，いまだ臨床応用には不十分であるため，さらなるシステムの改善が必要である．おもな誤差要因には，レジストレーション誤差，トラッキング誤差，関節鏡カメラ校正誤差，プローブでのディジタイズ誤差の４つがある．予備実験の結果などから，その中でもレジストレーション誤差が最も大きいと考えられる．そのため，レジストレーション手法の改善が当面の課題である．今後は，ACL再建術だけでなく，さまざまな関節鏡手術に応用を拡大したいと考えている．そのためには，軟骨や半月板といった軟部組織情報をもつMRIモデルも用いる必要がある．それも今後の課題である．

ま と め

我々は関節鏡視下手術の支援を目的として，骨モデルを術中の鏡視画像に重ね合わせて表示するシステムを開発してきた．今回，切断肢を用いてシステムの総合精度を評価した．その結果，誤差は平均1.95mmとなった．今後の課題は，レジストレーション手法の改善，軟骨を含むMRモデルの導入である．

文　献

1）平澤信，林豊彦 他：３次元コンピュータモデルと２方向X線像との重ね合わせを用いた人工関