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A postural program to reduce dynamic knee valgus during single-limb squatting in young athletes: a preliminary study

Postural program to reduce DKV in athletes

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Abstract

BACKGROUND: Dynamic Knee Valgus (DKV) is an undesirable multi-joint movement pattern associated with anterior cruciate ligament injury and patellofemoral pain syndrome, especially in sport activities. We assessed DKV in young athletes who followed a postural program to reduce a posterior rigidity mostly attributable to the tightness of hamstring muscles.

METHODS: We considered 12–18-year-old athletes that followed a six-week program simply based on hamstring stretching and abdominal muscle activation/strengthening. DKV was assessed during a single-limb squat and the frontal plane projection angle (FPPA) between the femur and tibia was considered.

RESULTS: Sixty-six athletes with a significant DKV (FPPA≥10°) were identified. Twenty-one subjects exhibited the considered rigidity profile and completed the intervention program. The mean reduction of the FPPA after the intervention was 8.1° (±7.9°), significantly asymmetric by about 3° (p<0.005) and skewed towards larger negative differences. The average change from the initial condition of -37% (±25%) was statistically significant (p=1.7x10-6).

CONCLUSIONS: This preliminary result suggests that working on enhancing posterior muscle chain flexibility could be effective in reducing DKV in young athletes with a marked tightness of hamstring muscles. Moreover, this simple postural program can be a candidate for inclusion in sport training as a protective strategy against knee injuries.

Key words: Hamstring Muscles; Muscle Stretching Exercises; Posture; Knee

Introduction

Dynamic knee valgus (DKV) is a movement pattern characterized by hip adduction, knee abduction and ankle eversion [1]

DKV contributes to anterior cruciate ligament (ACL) strain [2] and is associated with ACL injury [1,3] and patellofemoral pain syndrome (PFPS) [3,4]. Both ACL and PFPS are common in young athletes who practice jumping, cutting, pivoting, and single or double squatting and landing [5,6].

To date, there is no convergence on the causes that lead to DKV and several associated modifiable factors have been investigated [7,8], as reported below: a) an increase in passive hip external rotation range of motion (ROM) - possibly due to its influence on joint stability during weight-bearing activities; b) a reduction in trunk side-bridge strength - i.e., a combined effect of lateral flexion strength of the trunk and hip abductor strength [9]; c) a reduction in gluteus maximus activation - hip extensor and involved in hip external rotation [10]; d) a reduction in passive ankle dorsiflexion ROM assessed with the knee extended – this, in fact, may lead to DKV due to its association with peak landing force and increased foot pronation which, in turn, may increase the risk of knee abduction during movement; furthermore, a reduced passive ankle dorsiflexion is suggested to limit knee flexion during weight bearing, leading to a compensatory increase in knee abduction [11]. Conversely, weaker hip abductors (mainly the gluteus medius), external rotators and extensors, and knee flexors are at most weakly associated with the increase of this pattern.

Current approaches to reduce DKV are mainly based on muscle strengthening and/or neuromuscular control, with or without muscle lengthening, all addressed the lower limbs, to improve motor control. Stickler and colleagues systematically reviewed the impact of hip strengthening and/or neuromuscular control on frontal plane knee mechanics in females [12]. They found no significant evidence for the use of lower extremity strengthening alone to change knee valgus during a jump task. Conversely, neuromuscular control, either alone or in combination with strengthening exercises, had a positive impact on varying outcome measures, including DKV. Other interventions resulting in a DKV reduction combined muscle lengthening with neuromuscular control, with or without muscle strengthening [13–15].

The heterogeneity of the identified modifiable factors and proposed intervention programs, suggests that DKV can be a multi-joint movement pattern that involves trunk and lower limbs in all the three planes of the space, which led us to approach it as a problem of postural control.

The CPM – Canali Postural Method® (CPM) is a local method also applied to elite athletes worldwide [16]. For the CPM, posture stability in dynamic situations mainly relies on abdominal, hamstring and shoulder stabilizer muscles. In particular, CPM considers the importance of the abdominal muscles for the stabilization of the pelvis during movements that alternate flexion and extension of the hip with a loaded limb as these imply controlling a shift on the sagittal plane and a tilt of the pelvis. At the same time, during such movements, the abdominal muscles also support the rib cage in its role of stabilizing the spine. A key role in the stabilization of the pelvis, in terms of tilting and consequent modulation of the lumbar load, is also obtained through hamstring muscles. These, if recruited in synergy with abdominal activation, act as the main extensors of the hip and are consequently involved in movements of the lower of limbs along the sagittal plane. Finally, shoulder stabilizer muscles are crucial for maintaining optimal function of the shoulder joints especially in the elevation of the upper limbs.

As also recognized by Powers, the stabilization of the pelvis and trunk may not be sufficient to counteract the stresses from incorrect movement patterns of upper and lower limbs, especially in the case of weakness or tightness of involved muscles [17]. In such cases, in fact, hip and trunk may shift and rotate to reduce the demand on those muscles not able to fully execute the demanded task. In turn, this protective postural arrangement, far from solving the problem, may determine a non-physiological stress on other districts [17]. During single limb squat (SLSs), addressed in the present study, we assume that a hip adduction can occur when the posterior muscle chain cannot lengthen sufficiently. This may be due for the tightness of hamstrings. All these issues should be considered due to the fact that an SLS leading to DKV involves postural adaptations along the three planes.

As a general approach, CPM, consistently with the synergistic muscular activations previously described, bases intervention strategies on increasing the concentric and eccentric strength and / or length of specific muscles identified as the last responsible for a particular incorrect movement, concomitantly with strengthening the abdominal muscles [16–19]. The CPM uses individualized gymnastic exercises that can be framed within the sport sciences and does not provide for manual therapeutic interventions typical of physiotherapeutic approaches, therefore it cannot be used for the treatment of pathologies.

Based on the above reported considerations, we designed a simple gymnastic exercise program for hamstring tightness reduction based on the exercises proposed by the CPM [16]. The lengthening of hamstring muscles requires a specific attention that depends on the tightest area (central, medial, or lateral) and on the position of the limb in the horizontal plane (neutral, intra- or extra-rotated) that mostly emphasizes it. In order to prevent bias, we chose to focus only on the tension perceived in the central and/or lateral areas that resulted from a neutral or intra-rotated position of the limb if such tension prevails over the one perceived in the medial area in any other position. Moreover, due to their role in trunk stabilization, exercises for strengthening abdominal muscles were also included.

The study was focused on young athletes with an evidence of DKV and who exhibited the lowest hamstring flexibility when the limb was in a neutral or intra-rotated position and tension was perceived in the central or/and lateral area.

The DKV was assessed during a SLS as this is usually adopted for functional movement examinations [20], including DKV assessment, it is a common task for young athletes [21], and requires great hip muscle control [22] that can reveal incorrect dynamics of lower extremities.

The aim of this preliminary study was to verify the presence of changes in DKV in the target subjects after the application of a simple and short postural program based on CPM, in addition to the regular training, designed to reduce a posterior rigidity mostly attributable to the tightness of hamstring muscles.

Materials and methods

Participants

A convenience sample of eighty-four volleyball and track and field athletes aged 12–18-year-old were considered for enrolment in the study.

The criteria for inclusion were: A) presenting DKV in at least one limb (the arbitrary threshold of ≥10° was assumed to identify most relevant cases; the way in which this angle is calculated is described further on); and B) exhibiting the most reduced hamstring flexibility, when the limb is in a neutral or intra-rotated position and tension is perceived in the central or/and lateral area.

The criteria for exclusion were: A) having a history of lower extremity surgery; B) presenting a lower extremity injury within three months prior to the data collection; and C) attending less than 75% of the planned workout sessions.

The participants and their parents were informed about the study and signed a consent form. The study was conducted in accordance with the principles set forth in the Helsinki Declaration. The study protocol was approved by the research ethics committee of the National Research Council of Italy (Protocol number 0012630/2019). Additional consent was granted to include photos in this paper.

Assessment procedures

The athletes' height and weight were measured. All subjects performed a standardized warm-up program for a maximum of 10 minutes: 5 minutes of running, followed by shoulder mobility exercises, stretching of the gastrocnemius muscles with extended and flexed knee, and 2x5 repetitions of double squats and 2x3 repetitions of double squat jumps. Apart for the warm-up, the participants were barefoot and wore shorts.

Hamstring tightness

Hamstring tightness was assessed through an easily performable test described in Canali [16] and here briefly reported. Subjects were asked to: sit on a step of 30 centimeters in order to relieve any possible tension induced by the posterior chain rigidity on the lower extremities; extend one limb, whose ankle is passively dorsiflexed; and keep the other limb wide apart. From this position, keeping their back straight and their pelvis anteverted, subjects sequentially flexed their trunk toward the extended limb in the neutral (Figure 1A), intra-rotated (Figure 1B), and extra-rotated (Figure 1C) positions, until they begin to perceive tension. The angle reached was visually evaluated by the operator; for the rigidity assessment, the operator identified the position with the smallest angle. In this position, the muscle area where tension was perceived (central, medial, or lateral) was considered the tightest. This area and the positioning of the lower limb constituted the tightness profile of the hamstring muscles. The test was executed for both limbs.

[Figure 1]

DKV

DKV was assessed during a SLS, as previously described by Schmidt et al.: while maintaining balance, subjects were instructed to squat as deeply as and return to the upright stance [23]. To familiarize themselves with this task, participants performed three preliminaries SLSs for each leg. Two-dimensional (2D) video motion analysis was considered to assess the frontal plane projection angle (FPPA) between the femur and tibia was considered [24,25]. Two markers were placed on the anterior superior iliac spines and the tibial tuberosities of the subjects, and the location of the center of the ankle was considered as well. The SLS was captured using a video camera (Canon EOS 4000D) frontally placed 2.0 m from the subject at the height of 0.52 m from the ground. The recorded videos were analyzed on a computer using the Kinovea video analysis software [26,27] to calculate the FPPA, at the frame in which motion reversal occurred between the descent and ascent phases of the SLS (Figure 2).

[Figure 2]

Intervention

Athletes followed a six-week program (7–10 minutes per session, twice a week). The simple intervention program was based on one self-executed (but supervised) exercise in a pool of four for stretching the hamstring muscles (Figures 1A or 1B, 3A-N or 3A-I, 3B, and 3C), and one exercise for the activation and strengthening of the abdominal muscles, executed with the assistance of the trainer (Figures 3 D-N and D-I). To be noted, Figure 1C is not adopted as exercise due to the specific profile of the included subjects. The athletes executed three series of one activation/strengthening exercise (20 seconds the first week, with a 5-second increase each week) and three stretching exercises (10 seconds, with a 30-second rest between each). The latter was applied only on the limb presenting DKV (FPPA≥10°). Details are reported in the Supplementary Digital Material (Supplementary Text File).

[Figure 3]

The trainers of the athletes were instructed (including an individual theoretical session) by the principal investigator, who is trained in CPM. Moreover, they were supervised during the first week of application on athletes.

Statistical Analysis

As DKV was assessed at two subsequent times on the same subjects, the sample of differences in FPPA (i.e., post- minus pre-intervention) has been analyzed. A study to determine an approximation of the necessary sample size was carried out even in this framework of convenience sampling. An initial estimate of 40 enrolled athletes and a dropout rate of 25% [28] suggested a sample of 30 subjects. According to standard methods for random samples and considering a difference of 3° as important [29], a power of 80% was reached at the 5% significance level if the standard deviation of the differences was <5.86°.

Summary statistics have been computed. Then, Gaussianity of the differences was checked by the Shapiro-Wilks test. If the Gaussianity assumption was rejected, the non-parametric Wilcoxon sign test was carried out in place of the t-test. A difference of 3° was considered as significant [29]. Relative variations with respect to the initial condition were analyzed as well. In this case, after testing for normality, the two-sided hypothesis was considered. Finally, the association between differences in FPPA and gender or type of sport activity was analyzed by either the t-test or the Mann-Whitney test when Gaussianity was rejected. If a subject presented DKV in both the limbs, the one where the FPPA has decreased less was considered. A significance level of 0.05 was considered. All analyses were carried out by software R [30].

Results

Eighty of 84 screened athletes presented a DKV (66 with FPPA≥10°). Thirty-two were found with a posterior/posterolateral hamstring tightness profile and were included in the exercise program. Due to a 34% dropout (2 athletes were injured during sport activities and 9 have left their sport during the course of the study), 10 volleyball and 11 track and field athletes (10 females, age 15.0 ± 1.60 years, height 1.64 ± 0.09 m, weight 53.4 ± 10.11 kg, initial FPPA 20.0 ± 9.3 degrees) were included having completed at least 75% of the intervention program. Seven out of 10 females were volleyball athletes while almost all the boys (8/11) were track and field athletes. Regarding their sport activities, the weekly training time was 6.3 hours. Moreover, among the 21 athletes, 2 were overweight, ac-cording to the definition of BMI for age [31].

The scatter plot of post versus pre FPPA values is shown in Figure 4. This latter highlights that all but two subjects reduce the FPPA value, 15 improve by at least 3° (the value assumed to be significant) and 7 out of 21 have removed the problem reporting a post-treatment DKV below the inclusion threshold of 10°. Both the distributions of pre and post values present outliers, marked in Figure 4 by diamonds.

[Figure 4]

Three of 21 subjects presented DKV in both the limbs.

The mean (±SD) of the difference of the FPPA was -8.1° (±7.9°) and the median was -6° (inter quartile range from -11° to -2°). All the subjects had a decrease in DKV, except for one, whose FPPA increased by 1 degree. The difference was not significantly associated with gender or type of sport ($p>0.34$) and no correlation with age was found ($\rho=-0.11$, $p=0.63$). This univariable analysis was also confirmed by an explorative multivariable regression analysis (multiple R-squared: 0.07166, adjusted R-squared: -0.09217; p-value: 0.73). Similar analyzes were conducted on the initial data with completely similar results. Figure 5 shows both initial data (5a) and final differences (5b) by sex. In both cases, the between genders differences are not statistically significant ($p>0.30$).

[Figure 5]

The FPPA differences are asymmetrically dispersed, as confirmed by the quite large and negative skewness (-1.43). Moreover, these differences show a high positive kurtosis (5.10), therefore suggesting lack of normality. This was confirmed by the Shapiro-Wilks test (p = 0.01) and hence non-parametric tests were adopted for the analyses. According to the Wilcoxon test, the distribution of FPPA differences was significantly asymmetric by about 3° (p <0.005). As previously mentioned, 15/21 subjects (71%) had the improvement of more than 3° that has been assumed as important in the section 2.4. A significant difference is also obtained in both groups of male and female (p<0.05).

Since the FPPA after the intervention seemed to have a quite strong negative correlation with the angle at the baseline (-0.79), we also considered the relative variation. Relative differences were mainly negative and quite symmetric (skewness = -0.02, kurtosis = 1.99), supporting the assumption of gaussianity confirmed by the Shapiro-Wilks test (p=0.68). The two-sided t-test strongly rejected the null hypothesis of no improvement after treatment with respect to the initial FPPA value (p=1.7 x 10-6). The mean (±SD) relative variation was -37% (±25%).

Discussion

The purpose of this preliminary study was to investigate if DKV during SLS could be decreased in young athletes with hamstring muscles tightness in the central or lateral areas, following a six-week postural program in addition to their regular training. The result suggests that working to reduce this tightness, in combination with the activation/strengthening of abdominal muscles, could be effective in reducing the DKV: the mean FPPA decrease was equal to 8.1° and the mean FPPA relative variation was equal to 37%.

When comparing our work with other studies with the same objective, several differences can be highlighted with respect to the target muscles and the nature of the intervention, the coherent selection of the subjects with the hypothesized cause, the way in which exercises were executed, and the duration of the intervention. With specific reference to the lower extremities, we focused on the lengthening of hamstring muscles. To our knowledge, there is no study in literature that has explicitly considered the tightness of these muscles as a modifiable factor associated with DKV [7]. Nevertheless, some researchers have considered the lengthening of hamstring muscles in the proposed intervention programs aimed to reduce DKV [13–15]. These studies, unlike ours, adopted wider programs that combined lengthening, strengthening and neuromuscular control exercises focused on hamstrings, as well as other muscles in the lower limbs; moreover, we have not found any mention of the possible role of the hamstring muscles tightness in DKV. However, according to CPM and similarly to Bell et al. [13], intervention strategies combine muscles lengthening and strengthening. As a first step, in fact, CPM aims to increase the subject's ability to statically support the desired movement (thanks to the work on intermediate postures that get closer and closer to the target final position to be used in dynamics. In this phase, muscle strengthening is achieved through isometric contractions with gradually increasing load, in the initial part of the exercise, and iso-metric isotonic contractions, in the remaining. However, unlike Bell, we have not worked on strengthening the muscles of the lower limbs but we focused on the activation/strengthening of abdominal muscles, which are considered by the CPM as a core component of any postural program due to their role in pelvis and spine stabilization in the sagittal plane. Working in this plane becomes essential as it is the first to be involved during the execution of a SLS. Conversely, as well argued by Powers [17], aberrant movements of the trunk, also due to weak abdominal muscles, can influence the moments acting on the knee during single-limb activities.

According to the CPM, since compensations start in the sagittal plane, postural interventions should start from this plane, thus we focused on the strengthening of abdominal muscles in this study. We believe that a more complete and longer postural program with the objective to completely solve the problem, which was out of the scope of the present preliminary study, should address any residual compensation within the other planes.

From a motor control perspective, an insufficient elongation of the hamstring muscles is a negative factor in activating the correct motor control strategies during functional tasks involving lower limbs. Consequently, stretching exercises could indirectly improve motor control capacity. This control, as also pointed out by Powers [17], can be further improved by acting on the stabilization of the abdominal muscles.

Several novel elements characterize the proposed program of exercises. The subjective selection of the stretching exercise out of the proposed pool (Figures 1A or 1B, 3A-N or 3A-I, 3B, and 3C) allows to ensure stretching effectiveness in the desired target (i.e., hamstring muscle belly). The execution of abdominal strengthening in the body positions in which these will be needed (Figures 3D-N or 3D-I); this is obtained with the use of an inclined plane that, according to the progresses of the subject, allows to change the degree of hip extension, asking the subject to perform and anterior tilt of the pelvis. To better allow the activation of new motor control strategies, the stretching (improving the functioning of the hamstrings) and strengthening (improving the functioning of the abdominal muscles) is continuously alternated due to the synergic involvement of these two muscles in the SLS. The final result is a global stabilization during the SLS that allowed the subjects to reduce an aberrant movement such as the DKV, thanks to the possibility of resorting to new or improved motor control strategies.

A further issue of our study was the selection of athletes with DKV and a specific postural profile. We considered subjects with the lowest hamstring flexibility when the limb was in a neutral or intra-rotated position and perceived tension in the central or/and lateral area. This represents our hypothesis that such reduced muscle chain flexibility due to hamstring tightness could be a possible cause of DKV, which determined the set of exercises chosen for the intervention. Other profiles of hamstring muscle rigidity could possibly lead to DKV but were not considered in this study; these are different combi-nations of the tightest muscle area (central, medial, or lateral) and the position of the limb in the horizontal plane (neutral, intra- or extra-rotated) that mostly emphasizes it. These profiles need to be managed with a specific set of exercises different from the one considered in the present work. In the current literature, we have not found any indication of a similar approach to selection, except for the study by Bell [13], where subjects with DKV were also selected for their weak ankle plantar flexors and the intervention program included a specific exercise to strengthen these particular muscles. The detailed planning of exercises based on the specific subject's postural profile is one of the two pillars of the proposed methodology that contributes to create a personalized approach.

The other important pillar of personalization is the way any selected exercise is performed in each work session. During the execution of exercises, the athletes were always solicited by their trainers to maintain a constant attention on perceiving the tension/contraction only in the belly of the muscles to be stretched/strengthened. Corrective actions such as changing exercises or using facilitators were taken as soon as deviations from the right targets were noted. To our knowledge, no investigators have explicitly reported a similar approach.

With respect to the duration of the intervention, it should be noted that our simple postural program consisted of two types of exercises designed to be completed in only 10 minutes per session (approximately 20 min a week) in the last week of the intervention, which was a shorter time frame as compared to other studies [13–15]. This short time could be a very relevant feature for the possible inclusion of the proposed intervention in a sport training work session (in the warm-up or cool-down phases, for example).

The results of this study should be considered in light of its limitations: 1) the use of a method not yet validated, although widely used nationally and also applied to elite athletes worldwide; 2) the absence of an age-matched control population, but it should be noted that comparable studies reported no significant variations of DKV in their control groups [14,32–34].

Moreover, the actual reductions of hamstring muscles tightness and the increases of abdominal muscles strengthening were not quantified and are assumed as an expected result of the proposed exercise program.

An additional limitation was the presence of subjective quantifications. With regard to the detection of hamstring tightness, although the methods for assessing external measurements and internal perception are objectively defined in Canali V. [16] and reported in the paragraph on hamstring tightness, their application was obviously subjective. Nevertheless, this was a minor limitation because we were not interested in the quantification of the hamstring tightness but only in definition of the tightness profile for the inclusion purpose. With respect to the quantification of DKV which is partly subjective, we adopted aids (markers and software) to minimize the risks of inaccurate measurement. Although three-dimensional (3D) motion analysis is considered the gold standard methodology for kinematic analysis, when considering the assessment of knee motion, it has been found that two-dimension (2D) FFPA measures have a good correlation with knee abduction angles in 3-D during SLS [24]. FPPA is a commonly used alternative also thanks to its lower cost, ease of implementation, and readily available measurements [4,25,35]. The choice of the 10° threshold on FPPA for inclusion, while allowing to address the most relevant cases – that is the subjects who can derive the maximum benefit from an improvement in DKV – could have led to an overestimation of the average absolute effect size (FPPA difference) or to hide any subjects who may have experienced a worsening of the condition after treatment. While recognizing the arbitrary choice of the threshold, we believe that our approach brings our study closer to a real scenario in which corrective interventions are proposed only to subjects with a relevant manifestation of a postural problem. The FPPA was calculated only at the moment in which motion reversal occurred between the descent and ascent phases of the SLS without considering the starting point in standing position. This approach, although consistent with similar published studies [13–15] may have introduced bias in the preliminary and secondary analyses (Table 1, Figure 4, Figure 5a, univariable analysis and explorative multivariable regression analysis on initial data). While the analyses of absolute differences are obviously not affected by this choice, we cannot of course exclude possible variations in those based on relative differences if we had also adopted the alternative approach of including FPPA measures in the initial standing position. Moreover, the sample size hypothesized based on a traditional power analysis was not achieved despite great efforts to recruit participants. This was due to a drop-out greater than assumed because of the abandonment of sport, the limitation of the specific tightness profile and an actual standard deviation higher than the assumed one. The small sample size, and even before the fact that a convenience sample was considered, prevent any extension to any larger reference population. Finally, the possible dependence of the results on some covariates can be hidden. The sample was heterogeneous in terms of age, gender and type of sport. However, FPPA variations were neither significantly associated with gender or type of sport nor correlated with age. In addition, the pre-post assessment allows for a perfect control of these covariates. Of course, future validation studies should duly consider these potentially confounding factors.

Despite such limitations, to our knowledge, this is the first preliminary study that, with the regard to lower extremities, based the intervention on only the lengthening of hamstring muscles and on a specifically selected rigidity profile among those that have DKV. Then, we believe that the results obtained in this preliminary study also contribute to the definition of new sound hypotheses for further studies.

Conclusions

This preliminary study shows that working on enhancing posterior muscle chain flexibility could be effective in reducing DKV in young athletes with a posterior rigidity profile mostly attributable to the tightness of hamstring muscles.

We think that this simple postural program based on hamstring stretching and abdominal muscle activation/strengthening can be a candidate for inclusion in sport training as a protective strategy against knee injuries.

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TITLES OF FIGURES

Figure 1.— *Figure 1. Hamstring muscle tightness test and stretching exercise 1. A band, placed around the left lower limb, is used to passively dorsiflex the ankle (a) and in a neutral, (b) intra-rotated, (c) and extra- rotated position.*

Figure 2. — *The frontal plane projection angle (FPPA) between the femur and tibia.*

Figure 3. — *Stretching and activation/strengthening exercises. (a), (b), (c): Hamstring muscle stretching exercises. Subject places left lower limb on the step in a neutral (a-n) and intra-rotated (a-i) position. (d): Exercise for the activation and strengthening of abdominal muscles. The subject's left lower limb is in a neutral (d-n) and intra-rotated (d-i) position.*

Figure 4. — *Scatter-plot of post versus pre values of the FPPA. Dashed gray lines indicate the threshold of significance (10°) adopted in this study. The black continuous*

line is the bisector of the quadrant. The points in the gray zone correspond to subjects with an important significant improvement. Diamonds highlight outlier values.

Figure 5. — *(a) FPPA value by sex (pre-intervention, degrees); (b) FPPA variations by sex (post- mi-nus pre-intervention, degrees).*