Assessment of Relationships Between Joint Motion Quality and Postural Control in Patients With Chronic Ankle Joint Instability

Individuals who participate in recreational and full-time sporting activities are particularly susceptible to injuries, among the most common being lateral ankle sprain (LAS). Depending on the degree of injury, LAS may lead to varying periods of immobilization and absence from desired physical activity. Although ankle sprains are often considered to be innocuous injuries, approximately 30% to 70% of people who suffer a single acute LAS will suffer a recurrent sprain, and they may experience ankle pain and instability for over a year.

Many categorical descriptions have been used to define this pathology, including recurrent ankle instability and chronic ankle instability (CAD). The factors contributing to CAI have traditionally been separated into mechanical (range-of-motion deficits, arthrokinematic alterations, ligamentous laxity) and functional impairments (sensorimotor deficits that impair stability during functional activities). However, it should be noted that most patients with symptoms of ankle functional instability have no clinical evidence of mechanical instability. Therefore, the analysis of functional instability, rather than of mechanical instability, has been postulated for defining CAI in clinical practice.

Despite the wide range of techniques that have been employed to examine functional instability of the ankle, the best indication of changes in sensorimotor system function could be provided by postural control analysis, especially in dynamic conditions, where major involvement of the sensorimotor system is needed.

STUDY DESIGN: Controlled laboratory study, cross-sectional.

BACKGROUND: Lateral ankle sprains are among the most common injuries encountered during athletic participation. Following the initial injury, there is an alarmingly high risk of reinjury and development of chronic ankle instability (CAI), which is dependent on a combination of factors, including sensorimotor deficits and changes in the biomechanical environment of the ankle joint.

OBJECTIVE: To evaluate CAI-related disturbances in arthrokinematic motion quality and postural control and the relationships between them.

METHODS: Sixty-three male subjects (31 with CAI and 32 healthy controls) were enrolled in the study. For arthrokinematic motion quality analysis, the vibroarthrographic signals were collected during ankle flexion/extension motion using an acceleration sensor and described by variability (variance of mean squares [VMS]), amplitude (mean of 4 maximal and 4 minimal values [R4]), and frequency (vibroarthrographic signal bands of 50 to 250 Hz [P1] and 250 to 450 Hz [P2]) parameters. Using the Biodex Balance System, single-leg dynamic balance was measured by overall, anteroposterior, and mediolateral stability indices.

RESULTS: Values of vibroarthrographic parameters (VMS, R4, P1 and P2) were significantly higher in the CAI group than those in the control group (P<.01). Similar results were obtained for all postural control parameters (overall, anteroposterior, and mediolateral stability indices; P<.05). Moreover, correlations between the overall stability index and VMS, and P1 and P2, as well as between the anteroposterior stability index and P1 and P2, were observed in the CAI patient group, but not in controls.

CONCLUSION: In patients with CAI, deficits in both quality of ankle arthrokinematic motion and postural control were present. Therefore, physical therapy interventions focused on improving ankle neuromuscular control and arthrokinematic function are necessary in CAI patient care.
chondral stress.22,23,43 These mechanisms seem to accelerate cartilage wear and degeneration, which are manifested as a deterioration in quantitative and qualitative aspects of joint motion.46 In contrast to assessment of quantity of joint motion via range-of-motion measurements (using a goniometer, arthrometer, or inclinometer), the qualitative analysis of arthrokinematic motion is highly subjective in nature.59 This evaluation focuses on the integrity and smoothness of motion with regard to the presence or absence of crepitations (mechanical oscillations and sounds produced by articular surfaces). It has been postulated that this phenomenon is associated with impairment of both the condition of the articular cartilage and arthrokinematic function.7 Despite the fact that knee crepitus is included in the gonarthrosis diagnostic criteria of the American College of Rheumatology (with sensitivity and specificity of 1.0 and 0.94, respectively), crepitation occurrence within the ankle joint is practically unrecognized, although 18% of patients with CAI report this phenomenon.58,59 Therefore, there have been calls for the development of more specific methods to evaluate the quality of arthrokinematic motion.24,32

One of the novel methods developed for more sensitive and objective assessment of articular function related to crepitus occurrence is vibroarthrography (VAG). This noninvasive method is a helpful tool for physical examination that could evaluate the arthrokinematic motion quality using accelerometers placed on adjacent anatomical structures.35 Sensors register a high-frequency vibroacoustic emission, which is a natural phenomenon acquired from relative motion of articular surfaces. A physiological hyaline cartilage (smooth and well lubricated) creates a nearly frictionless surface during arthrokinematic motion and generates slight, impalpable, and inaudible vibrations that are measurable by the VAG method. In contrast, in pathological conditions (eg, chondral lesions/stress, altered biomechanical environment), movement of articular surfaces is accompanied by significant vibrations and sounds (in clinical practice, known as crepitation). All categories of vibroacoustic emission during joint motion can be registered using the VAG method, and the intensity as well as waveform pattern of recorded signals seems to be associated with the condition of the joint structure. It was shown, especially for the knee, that VAG signals from abnormal joints possess a different waveform pattern and higher values of parameters than those from healthy joints.24,32 However, VAG data from arthrokinematic motion quality within the ankle joint are not available in the literature.

Therefore, an analysis of the condition of ankle motion quality by VAG assessment is highly relevant. The purpose of this study was to evaluate the arthrokinematic motion quality of the ankle in healthy subjects and patients with CAI. In addition, ankle neuromuscular control assessed by dynamic balance will be evaluated, and its relationship to ankle motion quality will be determined. Findings could broaden the knowledge about CAI-related restriction in ankle function and contribute to improvement of medical care, especially using appropriate techniques of physical therapy for patients with CAI.

METHODS

Study Population

The study group included 31 males who played either volleyball or basketball recreationally (about 4 to 5 hours a week) and were members of the university sports associations. For the study group, we recruited individuals who fulfilled the following inclusion criteria, in accordance with the endorsed minimal criteria of the International Ankle Consortium for CAI:22 (1) at least 2 significant LAS, classified as second degree in accordance with the American College of Foot and Ankle Surgeons,45 that were manifested by inflammatory symptoms (pain, swelling) and caused at least 3 interrupted days of desired physical activity; (2) LAS episodes occurred at the same joint (recurrent sprain) within a year and caused self-reported CAI, which was specifically confirmed by the Cumberland Ankle Instability Tool (CAIT) with a score less than 24.15

Exclusion criteria were a history of fractures and surgery of the musculoskeletal structures in either limb of the lower extremity, and a history of acute injury in other joints of the lower extremity in the previous 12 months that resulted in at least 1 interrupted day of desired physical activity. Moreover, individuals with pain and/or a limited range of motion in the assessed ankle joint, as well as with a history of diagnosed syndesmosis injury, were not included in the study.

As a medical intervention, after each injury classified by an orthopaedist as a second-degree LAS, 10 to 14 days of immobilization by either semi-rigid or lace-up ankle braces was recommended. Then, all CAI participants underwent an outpatient, individual 2-week functional rehabilitation program conducted by the physical therapist, with the following tasks: range-of-motion restoration (if needed), muscle-strengthening exercises, and proprioceptive training. Subsequently, self-performed exercises were continued to prevent reinjury and to enable return to full daily activity and sport.

For individuals with CAI, the final qualification was carried out between 51 and 53 weeks after the most recent significant injury of the ankle using the CAIT. Patients who confirmed the feeling of instability (CAIT scores less than 24) were admitted to the assessments of quality of joint motion and postural control, which were performed the next day. In each participant, only the ankle that satisfied the inclusion criteria was analyzed, due to the different condition of the opposite limb (either no injury or an uncertain number and/or degree of injuries).

The control group consisted of 32 healthy males, with a level of sport activity similar to that of the CAI group. Individuals in the control group reported...
that they had neither a history of ankle inversion sprain nor other injury or pathology within the lower extremity that impacted joint integrity and function (eg, sprains, fractures) and resulted in at least 1 interrupted day of desired physical activity. Moreover, no ankle instability was reported on the CAIT, on which all controls obtained a score of 29 or greater. In the control group, both limbs were tested in random order. The dominant limb was evaluated with functional tests (ball kick and balance recovery after being pushed) in order to examine lateralization as a potential confounding factor.

For detailed characteristics of all subjects, see Table 1. Signed informed consent was obtained from all tested persons, and the rights of subjects were protected. The project was approved by the Opole Voivodship Ethics Committee.

Assessment of Arthrokinematic Motion Quality

Ankle joint function was assessed with the sensor placed on the lateral surface of the lateral malleolus, using double-sided adherent tape (Figure 1). The VAG evaluation of arthrokinematic quality of ankle motion was based on the test performed in the sitting position, with loosely hanging legs and the following motions repeated 4 times in a period of 6 seconds: (1) full ankle plantar flexion, (2) full ankle dorsiflexion, and (3) re-plantar flexion. The constant velocities of both plantar flexion/dorsiflexion motion and measuring condition were kept at 82 beats per minute with a metronome. The angle of the ankle joint was measured using an electrogoniometer, but because the VAG signal might be distorted by electrogoniometer placement, which could generate noise signal, this procedure was only used during determination of the experimental condition before relevant tests.

The VAG signals generated by motion of the ankle joint were collected using an acceleration sensor with a multichannel NEXUS conditioning amplifier (model 4513B-002; Brüel & Kjær Sound & Vibration Measurement A/S, Nærum, Denmark). The signals were recorded as a time series expressed in volts, with a frequency range of 0.7 to 1000 Hz and a sampling rate of 10 kHz.

Each result was high-pass filtered beyond the 50-Hz threshold, to minimize low-frequency movement artifacts. The obtained signals ranged from 50 to 1000 Hz and were described using 4 parameters. The variability of the VAG signal was assessed by computing the mean-square values of the obtained signal in fixed-duration segments of 5 milliseconds each, and then computing the variance of the values of the parameter over the entire duration of the signal (variance of the mean squares [VMS] parameter). Moreover, for signal amplitude analysis, the R4 parameter (mean of 4 maximal and 4 minimal values) was used. Because of 4 full flexion/extension motion cycles, the R4 parameter was calculated as the difference between the mean of 4 maximal and the mean of 4 minimal VAG signal values.1-3

The frequency characteristics of the VAG signal were examined by short-time Fourier transform analysis. The short-time spectras were obtained by computing the discrete Fourier transform of segments of 150 samples each, the Hanning window, and 100 samples of overlap of each segment. The spectral activity was analyzed by summing the spectral power of the VAG signal in 2 bands: 50 to 250 Hz (P1 parameter) and 250 to 450 Hz (P2 parameter).1-3

Assessment of Postural Control

Dynamic postural control was analyzed by measuring center-of-pressure displacement, using the Biodex Balance System SD (Biodex Medical Systems, Inc, Shirley, NY).4

The testing was performed without footwear in a single-limb stance in the central region of the platform, while the unsupported limb was kept in a comfortable position without contact with either the tested limb or the test platform. All participants were also instructed to keep their hands at their sides and look straight ahead at a point on the wall approximately 2 m away, at eye level.

After correct positioning of the subject on a locked platform, the platform was unlocked. After a 5-second period, data acquisition commenced and continued for 30 seconds, then the platform

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**TABLE 1**

<table>
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<tr>
<th>Participant Characteristics*</th>
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<tr>
<td><strong>Control Group</strong> (n = 32)</td>
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<tr>
<td>Age, y</td>
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<tr>
<td>Height, cm</td>
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<tr>
<td>Weight, kg</td>
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<td>BMI, kg/m²</td>
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<td>CAIT score</td>
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<td>Number of sprains1</td>
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**Abbreviations:** BMI, body mass index; CAI, chronic ankle instability; CAIT, Cumberland Ankle Instability Tool.

*Values are mean ± SD.

1Ankle sprain was defined as a sprain that occurred at the analyzed joint in the year prior to the last injury, resulting in at least 3 interrupted days of desired physical activity.
was locked again. Of the 12 levels of resistance, level 1 was used, at which the platform was most unstable. For maintaining balance, movements of the limbs and trunk were allowed during the test. However, the uplifted leg was held apart from the stance leg and platform, and volunteers were not permitted to touch the hand rails of the platform. A total of 3 trials were performed, and 10 seconds of rest was given between tests, during which the subjects supported themselves on the untested leg.

To describe the degree of platform tilt from the horizontal level during all motions performed in the test, the overall stability index (OSI) was used. The anteroposterior stability index (APSI) and the mediolateral stability index reflect the movements of the platform during the patient’s balancing in the sagittal and frontal planes, respectively. All parameters were expressed in degrees, and for analyzed parameters the mean value of 3 trials was calculated.

**Statistical Analysis**

Normality of the distribution was assessed with the Shapiro-Wilk test. Because of skewed distribution of VMS, P1, and P2 parameter values, they were analyzed after logarithmic transformation. Evaluation of all dependent variables was performed with analysis of variance, and then, for post hoc comparisons, the Tukey test for unequal sample sizes was used. For correlations between values of parameters describing postural control and the VAG signal, Pearson r tests were performed. The level of significance was set at P<.05. Statistical analyses were performed using Statistica Version 10 (TIBCO Software Inc, Palo Alto, CA).

**RESULTS**

As there were no significant differences between results obtained for dominant and nondominant limbs (data not shown), a calculation was performed together for both lower extremities.

For arthrokinematic motion quality analysis, representative VAG plots of recorded signals specific to healthy controls were characterized by both small amplitude and low variability (FIGURE 2A). In comparison to controls, patients with CAI generated a signal with higher amplitude and variability (FIGURE 2B), corresponding with significantly higher values of VMS and R4 parameters (TABLE 2).

Time-frequency analysis of the VAG signal showed differences between groups (FIGURES 2C and 2D). The mean value of the P1 parameter for the CAI group was 8.8-fold higher, and of the P2 parameter 19-fold higher, than in controls (TABLE 2).

In dynamic balance process assessment, the OSI was statistically significantly higher in the CAI group than in the control group. Similarly, parameters describing the process of maintaining dynamic balance in both sagittal and frontal planes (APSI and mediolateral stability index, respectively) were significantly higher in the CAI group in comparison to controls (TABLE 3). This is also illustrated by representative plots of center-of-pressure excursion, where the path in the CAI group is more scattered than in controls (FIGURE 3).

In addition, significant correlations between values describing the process of postural control and VAG signal parameters were found (TABLE 4). In the combined group of CAI patients and controls, the OSI and APSI were positively correlated with VAG frequency parameters (P1 and P2). However, after analysis in particular...
groups, no correlation was found in controls, but the OSI was positively correlated with the VMS, P1, and P2 parameters in the patients with CAI. Moreover, similar correlations between the APSI and both P1 and P2 were observed (Table 4).

**DISCUSSION**

This study examined the dynamic postural control and quality of ankle arthrokinematic motion in patients with CAI, and relationships between them. The study findings confirmed that patients with CAI show impairment of postural stability in comparison to controls. Furthermore, we found that the CAI-related deficits in postural control were accompanied by reduced ankle arthrokinematic motion quality.

It has been previously demonstrated that loss of sensory input from articular and peri-articular mechanoreceptors is a crucial factor contributing to ankle functional instability.15,16,31,34 In subjects with CAI, deteriorated postural control is also related to decreased strength and endurance of lower extremity kinetic-chain muscles and increased time of reaction, especially of the peroneal muscles.16,33,34 These mechanisms could explain the higher values of parameters describing the dynamic balance process in both sagittal and frontal planes that we observed in the CAI group, which seem to reflect impaired ankle neuromuscular control.19,37

Moreover, patients with CAI demonstrated higher values of VAG signal parameters in comparison to controls. Contrary to the "smooth" courses of signals generated by normal ankle joints, the pattern of CAI-related VAG signals was characterized by the presence of local and brief peaks, especially during the change of direction of motion, which were replicable in each flexion/extension motion cycle. The pattern determined higher levels of variability (VMS parameter) and amplitude (R4) of the VAG signal. Additionally, the time-frequency analysis showed that CAI signals have

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**TABLE 2**

| Parameters of Vibroarthrography Signal in Patients and in the Healthy Control Group* |
|------------------------------------------|------------------------------------------|----------------|
| Control Group (n = 64 Ankles) | CAI Group (n = 31 Ankles) | P Value |
| VMS, V | 0.00003 ± 0.00005 | 0.00958 ± 0.02415 | .007 |
| R4, V | 0.449 ± 0.321 | 2.072 ± 1.372 | <.001 |
| P1, Hz | 0.635 ± 0.601 | 5.392 ± 4.324 | <.001 |
| P2, Hz | 0.034 ± 0.021 | 0.265 ± 0.613 | .006 |

Abbreviations: CAI, chronic ankle instability; P1, power spectral density band of 50 to 250 Hz; P2, power spectral density band of 250 to 450 Hz; R4, mean of 4 maximal and 4 minimal values; VMS, variance of the mean squares.

*Values are mean ± SD from raw data.

**TABLE 3**

| Parameters of Dynamic Stability in Patients and Healthy Controls* |
|------------------------------------------|------------------------------------------|----------------|
| Control Group (n = 64 Ankles) | CAI Group (n = 31 Ankles) | P Value |
| OSI | 3.17 ± 0.97 | 3.87 ± 1.42 | .018 |
| APSI | 2.50 ± 0.85 | 3.02 ± 1.12 | .032 |
| MLSI | 1.57 ± 0.63 | 2.22 ± 1.29 | .006 |

Abbreviations: CAI, chronic ankle instability; APSI, anteroposterior stability index; MLSI, mediolateral stability index; OSI, overall stability index.

*Values are mean ± SD degrees.

**TABLE 4**

| Correlation Coefficients Between Values of Postural Control Parameters and Vibroarthrography Signal Parameters Across Combined Groups and Each Group Individually* |
|------------------------------------------|------------------------------------------|----------------|
| Vibroarthrography Parameter | | |
| | VMS | R4 | P1 | P2 |
| Correlations across combined groups | | | | |
| OSI | 0.35 | 0.30 | 0.36† | 0.37† |
| APSI | 0.29 | 0.26 | 0.33† | 0.30† |
| MLSI | 0.19 | 0.29 | 0.27 | 0.22 |
| Correlations across the CAI group | | | | |
| OSI | 0.40† | 0.30 | 0.37† | 0.44† |
| APSI | 0.35 | 0.24 | 0.37† | 0.36† |
| MLSI | 0.12 | 0.13 | 0.09 | 0.16 |
| Correlations across the control group | | | | |
| OSI | -0.07 | -0.17 | -0.13 | -0.08 |
| APSI | -0.09 | -0.14 | -0.09 | -0.07 |
| MLSI | 0.16 | 0.04 | 0.02 | 0.05 |

Abbreviations: APSI, anteroposterior stability index; CAI, chronic ankle instability; MLSI, mediolateral stability index; OSI, overall stability index; P1, power spectral density band of 50 to 250 Hz; P2, power spectral density band of 250 to 450 Hz; R4, mean of 4 maximal and 4 minimal values; VMS, variance of the mean squares.

*Values are r.

†P<.05.
higher frequency, which corresponds to higher values of P1 and P2 parameters (TABLE 2, FIGURE 2).

We hypothesize that the above-mentioned reduction in arthrokinematic motion quality may be related to several mechanical impairments proposed as contributing factors to CAI: increased anterior joint laxity and reduced posterior talar glide, probably as a result of restrictions in noncontractile tissues and degenerative changes in ankle-complex structure.\(^{20,42}\) Moreover, sprain-related injury of the lateral ligaments and other structures (eg, subchondral bone, subtalar ligaments, peroneal muscles) can alter the axis of ankle joint rotation.\(^{26,83}\)

All of the above-mentioned functional deterioration and changes in the biomechanical environment may cause chondral stress, friction increase, and impairments of arthrokinematic function reflected in VAG signal patterns. A similar VAG course was observed in a lateral patellar compression syndrome, where the abnormal VAG signal was explained as resulting not from eroded articular surfaces but from disturbance of a more functional character, such as nonphysiological articular surface tracking direction or locally increased compression of cartilage associated with a compensatory movement pattern.\(^{3}\)

On the other hand, we cannot preclude the association between CAI-related VAG signal pattern and lesions in, or the diminished condition of, hyaline cartilage covering articular surfaces of the ankle joint.\(^{20}\) A clear association between osteochondral lesions and ankle injuries has been postulated, and it has been demonstrated that up to 50\% of patients have a cartilage injury or bone contusion after the ankle sprain. In addition, the repetitive microtrauma observed in ankle instability has been suggested to play an important role in accelerated wear and chondral degradation.\(^{6,39}\) Nonetheless, no differences between patients with 2 episodes of LAS and cases characterized by 3 or more injuries were found in this study (data not shown). Moreover, biomechanical data support the hypothesis that the development of cartilage pathology could be associated with immobilization and inflammation within the joint after the injury. Studies in rat models found that 15-day immobilization of the ankle joint caused degeneration of articular cartilage.\(^{27,41}\) However, data about changes in articular cartilage of the human ankle following immobilization are not available.

After immobilization, many patients report popping, snapping, or grinding sensations that arise during joint movement. Additionally, in clinical practice, such crepitations are self-reported by patients with CAI.\(^{21}\) It is possible that the CAI-related reduction in arthrokinematic motion quality of the ankle observed in the present study may be a result not only of injury but also of immobilization/inflammation. It is known that this clinical phenomenon reflects a diminished condition of hyaline cartilage.\(^{2,3}\) Nonetheless, a limitation of our study is that chondral status was not assessed by a suitable imaging method, such as magnetic resonance imaging, and therefore could not be confirmed. Further research of arthrokinematic motion quality should include direct evaluation of hyaline cartilage condition to establish whether a relationship exists between chondral lesions and VAG signal course. Moreover, the repeatability of the VAG signal course has not been established, and subsequent studies must assess its test-retest reliability to confirm the clinical usefulness of this method.

To the best of our knowledge, this is the first study to examine the quality of ankle arthrokinematic motion by VAG signal evaluation and its relationship with ankle neuromuscular control assessed via dynamic postural control. Interactions between both factors were analyzed by correlation tests, which showed positive but weak correlations. Moreover, statistically significant results were observed only in the sagittal plane and, in addition to the general population, exclusively in the CAI group. Therefore, based on this observation, it is not possible to determine a cause-and-effect relationship between these factors. It appears that this comorbidity may be explained as a “vicious cycle” and/or synergistic relationship between the mechanical and functional alterations, which were simultaneously expressed in the deteriorated condition of the ankle joint causing CAI.\(^{20,27}\) However, the mechanisms leading to the observed phenomenon are still not clear, and future investigations are necessary.

The present results extend our knowledge of the consequences of ankle sprain and confirm the multifactorial nature of CAI, which is associated with accelerated wear of articular surfaces and results in further cartilage degeneration and end-stage development of osteoarthritis.\(^{26,40}\) Physical therapy plays a pivotal role in the
improvement of functional limitation via the symptomatic treatment and sensori-motor training, and techniques to restore proper joint play should be considered.\textsuperscript{23,28}

Among physical therapy procedures that may facilitate improvements in quantitative and qualitative aspects of motion, ankle joint mobilization techniques are recommended. Additionally, their clinical relevance could be supported by increasing the afferent input by stimulating articular mechanoreceptors, with better neuromuscular control as a consequence.\textsuperscript{29} Hence, there is an assumption that joint mobilization could reduce both mechanical and functional impairment, although the direct impact of these techniques on analyzed factors is not clear and requires further investigation.\textsuperscript{29} There is evidence to suggest that the analysis of both arthrokinematic motion quality and dynamic postural control may be a helpful tool to monitor the effectiveness of specific rehabilitation in CAI.

**CONCLUSION**

We found that subjects with CAI, in addition to showing impairment of postural control, were characterized by reduced ankle joint motion quality. The coexistence of disturbances in both analyzed factors could be explained by deficits in ankle neuromuscular control and the altered biomechanical environment of the joint.

**KEY POINTS**

**FINDINGS:** Chronic ankle instability (CAI) is multifactorial in nature, with the presence of a synergistic relationship between the mechanical and functional alterations. Reduced postural control and ankle arthrokinematic motion quality are present in patients with CAI compared to healthy controls.

**IMPLICATIONS:** Physical therapy interventions for patients with CAI are necessary and, in addition to symptomatic treatment, should be focused on improving impaired neuromuscular control and arthrokinematic function of the ankle joint, which may lead to accelerated wear of the articular surfaces and increased risk of osteoarthritis.

**REFERENCES**


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