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Dall' **esperienza** e dalla **collaborazione**
con l'Istituto Ortopedico Rizzoli

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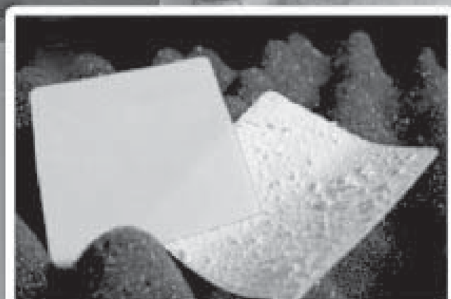

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BASIC SCIENCE

ANALYSIS OF COLLAGEN DISTRIBUTION IN ADULT PIG MENISCUS: A PILOT STUDY ANALYSIS OF THE THREE MENISCUS ZONES

E. BENASCIUTTI[1] and G. M. PERETTI[1,2]

[1]*Department of Biomedical Sciences for Health, University of Milan;* [2]*Unit of Regenerative and Reconstructive Orthopedics, IRCCS Istituto Ortopedico Galeazzi, Milan, Italy*

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Menisci are two semilunar fibrocartilaginous connective tissues located in the knee joint placed between the femoral condyles and tibial plateau. Their function is to allow the knee joint to perform fluid and controlled movements, and to absorb mechanical stresses resulting from flexion, rotation and mechanical loads. Meniscal cell populations and fiber distribution are differently organized within the tissue, in response to the load stimuli applied on the knee joint, resulting in an external region highly vascularized, an intermediate region less vascularized, and an internal region where blood vessels are absent. Since blood vessels are absent in the internal part of meniscus, when a lesion occurs in this region, the natural healing process very rarely takes place. Thus, in order to determine the most useful cell types involved in healing process, in this study we aimed to characterized collagen type I and II distribution in primary fibrochondrocytes extracted from the three meniscal regions of adult pigs. Analysis were performed by immunofluorescence and flow cytometry. We observed an increased concentration of collagen type I and a decreased distribution of collagen type II moving from the internal toward the external portion of the meniscus. The data confirmed the non-homogeneity of this structure in term of cell phenotype, which could be the results of the different biomechanical stimuli the menisci received in the different zones. Level of Evidence: 1 - Basic Science

Anatomy

The menisci are two semilunar fibrocartilage structures located medially and laterally between the femoral condyles and tibial plateau (1). The presence of menisci is fundamental for the correct function of the knee joint as they sustain and transmit mechanical loading, contributing to shock absorption, joint stability and lubrication (2-3).

By matching with the shape of the above femoral condyles, the menisci appear as wedge-shaped and slightly concave on their superior surface, presenting a thick external region. Together, the two menisci cover about two-thirds of the tibial plateau and are held in position through the attachments to the joint capsule and ligaments surrounding the knee (1, 4-6). These attachments keep the meniscus in the correct position during their radial and anteroposterior displacement according to the knee movements and provide the blood supply to the peripheral regions of the structure (2, 7).

Unlike articular cartilage, menisci possess an intrinsic innervation which is related to joint

Key words: knee, meniscus, collagen type I and II

Mailing Address: Prof. Giuseppe M. Peretti,
Head of the Unit of Regenerative and Reconstructive Orthopedics,
IRCCS Istituto Ortopedico Galeazzi,
Via R. Galeazzi 4, 20161 Milano, Italy
Tel.: +39 02 50319967 +39 02 66214735
Fax: +39 02 66214736
e-mail: gperetti@iol.it

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proprioception (8-9) mainly located in the anterior and posterior horns (10).

The human medial meniscus is vascularised for 10-30% of the total area, while the lateral meniscus for only 10-25%, being the blood vessels located in the external regions (7). Thanks to the vasculature, the external regions possess more healing ability following surgical suture than the internal regions probably due to the fact that cells cannot be recruited following injury or repairing procedure (1).

In the meniscus, 70-75% of wet weight is represented by water; 60-70% of dry weight is represented by collagens, 1% of proteoglycans and 8-13% of non-collagenous proteins, like elastin. Regarding the collagen component, about 90% is collagen type I, while the rest is type II, III and IV (7, 11-13).

The organization of collagen fibers shows that they are distributed mainly circumferentially and some of them are radially oriented. Probably, the fibers disposition is the result of the response to mechanical forces applied on the tissue. Moreover, collagen fibers are connected by elastin bonds. The presence of blood vessels restricted to the meniscal external region determines an inhomogeneity in tissue composition that can be easily detected by histological assays. The external vascularised meniscal region is composed by a fibrocartilaginous structure, while the internal avascular region is more similar to cartilage, presenting a different superficial portion that is similar to fibrous tissue.

Cellularity

Since the fibrochondrocytes function is to produce extracellular matrix, the lack of meniscal structural homogeneity is mainly due to a particular cellular distribution within its regions. Regarding cell morphology, cells in the superficial layers of the tissue are fusiform, whereas those located in the deeper zones are more polygonal (13).

Both cell types contain abundant endoplasmic reticulum and Golgi apparatus, while they possess only few mitochondria, suggesting that anaerobic glycolysis is the main source for ATP production. Anaerobic glycolysis may reflect the avascular environment surrounding fibrochondrocytes (13).

Cell morphology differs between the avascular internal region, where the cells are phenotypically similar to articular chondrocytes, to the external vascularised region, where the cells aspect is an intermediate between fibrocytes and chondrocytes. Due to their phenotype variability, meniscal cells are called fibrochondrocytes. These cells produce extracellular matrix, mainly represented by collagen type I and collagen type II. Meniscal collagen type I responds to mechanical traction, the same stimulus received by tendons; collagen type II, on the other hand, responds to compression, the typical stimulus on the cartilage tissue.

Repair studies

As described above, the meniscus is anatomically complex and it is populated by specialized cells with distinct roles.

The meniscus plays a key role in the stabilization of the knee joint as it is subjected to different mechanical stresses that may also be responsible for its lesions. While the original surgical intervention to approach meniscal lesions consisted in total meniscectomy, nowadays the importance of preserving as much healthy tissue as possible has been established. In fact, one consequence of total meniscectomy is the development of osteoarthritis within five-ten years from surgery (14).

Currently, many experimental approaches are being applied, in order to improve the biological bonding when tears are reparable (15), and to achieve the partial or total meniscus regeneration, when sub- or total meniscectomy are performed. From a clinical standpoint, partial meniscus regeneration represents a critical topic since the treatment of irreparable lesions of the avascular zone of the meniscus is still an open issue (16-17).

The pig is considered a valuable model for meniscal repair studies as it has been demonstrated that the vascularization of the porcine meniscus remains confined to the outer part of the menisci and not extending into the inner third of its structure. Additionally, the poor intrinsic reparative capacity of the meniscus in this animal model in the inner two-third resembles the situation typical in the human meniscus (15).

The correct approach for applying regenerative techniques for partial or total meniscus engineering to the porcine model first of all implies a deep knowledge of its anatomical structure and the extracellular matrix composition, together with the collagen fibre distribution in the three tissue layers. Starting from this assumption, in the present pilot study, we aimed to characterize the meniscal cell composition in the young adult pig in term of the different synthesis of the main collagens types I and II.

MATERIALS AND METHODS

Menisci preparation

Menisci were surgically harvested from four one year old female pigs euthanized for other study not related to this work, and stored at 4°C in sterile 1X Dulbecco's Phosphate buffered saline (PBS) (Life Technologies, Monza, Italy) additioned with amphotericin B (50mM) (Lonza, Milano, Italy), gentamycin (50mM) (Lonza, Milano, Italy), penicillin and streptomycin (100 U/ml) (Life Technologies, Monza, Italy). Medial and lateral menisci were pooled together assuming their similarities in cell phenotype and collagen composition in the different zones, based on unpublished data produced in our laboratory (data not shown). Each meniscus was cut into three portions (internal, intermediate and external) following the curvature of the perimeter and each portion was minced with a scalpel. The pieces were digested at 37°C, shaken for 22 hours in Dulbecco's modified minimum essential medium (DMEM) (Life Technologies, Monza, Italy), 5% v/v fetal bovine serum (FBS) (Euroclone, Pero, Italy), amphotericin (50mM), gentamycin (50mM), penicillin and streptomycin(100 U/ml), 0.15% collagenase type I (Worthington, New Jersey, US) and 0.15% collagenase type II (Worthington, New Jersey, US).

The cells were then passed through a cell strainer, centrifuged, resuspended in DMEM, 10% v/v FBS, sodium pyruvate (1mM) (Life Technologies, Monza, Italy), ultraglutamine (2mM) (Lonza, Milano, Italy), HEPES (10mM) (Life Technologies, Monza, Italy), amphotericin (50mM), gentamycin (50mM), penicillin and streptomycin (100 U/ml), seeded on tissue culture dishes and cultured for 48 h.

Immunofluorescence

40000 cells per well were seeded onto a multi-well glass slide for 1 hour, then fixed in cold 100% Methanol for 10 minutes. The cells were then permeabilized at room temperature (RT) in 0.1% Triton X-100, for 10 minutes, and washed with PBS 1X. Blocking was performed at RT in 10% goat serum, for 30 minutes. The samples were then incubated at RT for 1 hour with the following primary antibody, 1:50 diluted in 1% goat serum: Collagen I antibody rabbit (IgG) (Novus Biologicals, Milan, Italy); Mouse monoclonal anti type II collagen antibody biotynilated (Chondrex, Redmond, WA, US).

Incubation with secondary antibody was performed at RT for 1 hour with the following antibody, 1:1000 diluted in 1% goat serum: Goat anti-rabbit IgG (H+L) Alexa 488 (Life Technologies, Monza, Italy); Goat anti-mouse IgG (H+L) Alexa 488 (Life Technologies, Monza, Italy).

Nuclei were stained, for 10 minutes at room temperature, with Hoechst 333342 (Molecular Probes, Eugene, OR), 1:100 diluted in 1% goat serum. Negative controls were incubated with secondary antibody only, following the same protocol adopted for all samples. The glass slides were then analyzed at Leica confocal microscopy (TCS SP2 Laser Scanning Confocal). No signal was detected for negative controls.

Flow Cytometric Analysis

500000 cells per sample were fixed at RT in 75% Ethanol for 10 minutes. The cells were then permeabilized at RT in 0.1% Triton X-100 for 10 minutes and washed with PBS 1X. Blocking was performed in at RT in 10% goat serum, for 30 minutes. The samples were then incubated at RT for 1 hour with primary antibody, 1:50 diluted in 1% goat serum (see above). Incubation with secondary antibody was performed at RT for 1 hour. The antibodies were 1:200 diluted in 1% goat serum (see above). The samples were then run in BD Accuri C6 flow cytometer.

The data were analysed with FCS Express software for mean fluorescent intensity to quantify collagen type I and II, normalized for secondary antibody.

RESULTS

Cellular distribution of collagen type I and II

In order to understand and visualize the different cell types of the meniscus, such as those involved in the synthesis of collagen type I and II, immunofluorescence on primary fibrochondrocytes extracted from the tissue was performed. Collagen type I (Fig. 1A) was expressed by the cells of all the meniscal regions, but it was slightly more expressed by the cells of the internal and intermediate region, rather than the external.

A similar pattern was present also for collagen type II expression (Fig. 2A), which in the internal

Collagen type I

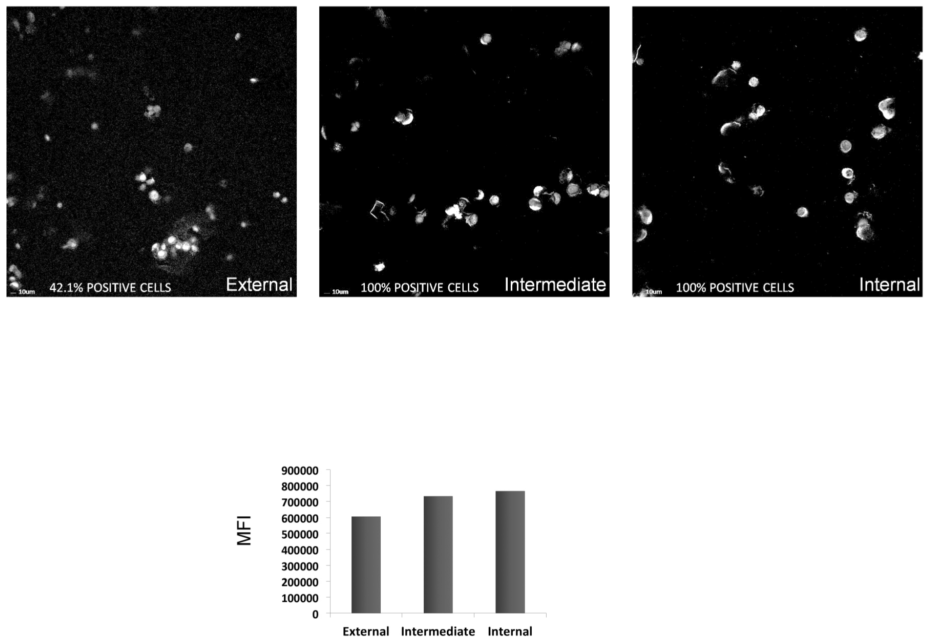

Fig. 1. ***A)*** *Immunofluorescence on primary adult pig fibrochondrocytes. The staining was performed on cells extracted from the external, intermediate and internal meniscal region. Red staining represents collagen type I and blue staining the nuclei.* ***B)*** *Flow cytometrical analysis of collagen type I expression, indicated as mean fluorescence intensity (MFI). The data are normalized on the isotype control.*

and intermediate region was comparable and intense, while it was faint in the external zone.

Quantification of collagen type I and II distribution

In order to quantify the collagen type I and II expression by meniscal fibrochondrocytes, a flow cytometric analysis was performed on the cells fixed and stained for each antibody, keeping the three regions distinct.

Collagen type I analysis showed a higher expression throughout the three zones with respect to collagen type II with a slight higher expression in the inner zone with respect to the intermediate and external ones (Fig. 1B) based on the date collected in this study.

Collagen type II expression (Fig. 2B) was greater starting from the external region, reaching its maximum level in the inner portion.

DISCUSSION

The preliminary data obtained in the present study show an increasing gradient in collagen type I distribution from the outer to the inner region of the meniscus both for collagen type I and for collagen type II in the young adult porcine meniscus model. These data confirm the non-homogeneous structure of the meniscus, and should represent the base of knowledge for any regenerative approach on this structure. In this study, however, only the amount of the intracellular collagen was analysed. This does not necessary duplicate the extracellular collagen present in the matrix. This may explain the inconsistency with a previous study which analysed the collagen type I

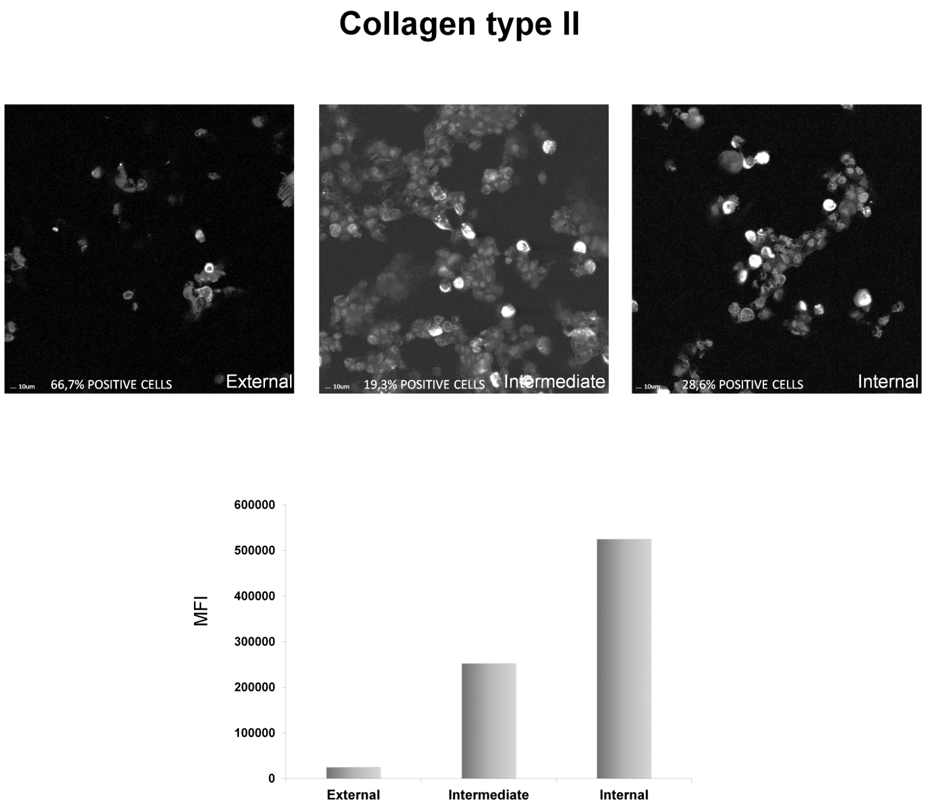

Fig. 2. ***A)*** *Immunofluorescence on primary adult pig fibrochondrocytes. The staining was performed on cells extracted from the external, intermediate and internal meniscal region. Green staining represents collagen type II and blue staining the nuclei.* ***B)*** *Flow cytometrical analysis of collagen type II expression, indicated as mean fluorescence intensity (MFI). The data are normalized on the isotype control.*

and II in the three zones in the extracellular matrix and where the collagen type I was not detected in the inner part of the meniscus (18).

Interestingly, we have noted a general higher concentration of collagen type I present in the cells in the three zones of the meniscus analyzed here, with respect to the expression of collagen type II. Additionally, we have also noted a slight increase of the collagen type I from the external to the internal zone, while this increase was much more pronounced for collagen type II, suggesting the need of a response for compressive load in the inner part of this important structure.

This preliminary data represent an interesting piece of information which suggests the different mechanical involvement of the three zones of the meniscus, which should be considered in regenerative medicine of the meniscus. However, if a tissue engineering approach for the regeneration of this structure is hypothesized, the cells derived from a biopsy of the meniscus would surely represent an insufficient cell source and would require an extensive culture expansion. Therefore, an analysis of the behaviour and the change of the collagen expression should represent the aim of a future study for any tissue engineering approach of this structure using meniscus cells. On the other hand, other cell sources could be considered, such as dermal fibroblasts or mesenchymal stem cells, which are more accessible and numerous. This cells could be directed by the use of different growth factors, biomaterials or mechanical stimuli towards the proper fibrocartilaginous phenotyte, which this study shows in the different zone of the meniscus.

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CASE REPORT

POSTERIOR STERNOCLAVICULAR DISLOCATION WITH LESION OF THE BRACHIOCEPHALIC TRUNK: CASE REPORT

F. LAMPERINI, G. RINONAPOLI, G. PLACELLA, P. ANTINOLFI and A. CARAFFA

Orthopedic and Traumatology Division, Santa Maria della Misericordia Hospital - University of Perugia, Perugia, Italy

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A 27-year old basketball player underwent a thoracic trauma during a regional championship match. The chest X-rays were apparently negative and the patient was dismissed from the emergency department. After one month, during another match, the man was hit in the posterior region of the shoulder, with consequent lipothymia and amnesia. Transported again to the emergency room, he underwent a thorax CT scan which revealed a postero-inferior dislocation of the right clavicle, with compression of the brachiocephalic trunk. He was operated in emergency by both the vascular surgeon, who removed the embolus and implanted a covered stent in the brachiocephalic trunk, and by the orthopedic surgeon, who reduced the dislocation and stabilized it with a 35 mm cross-carved plate (Synthes ®) in titanium, opportunely modified in order for the plate to better adhere to the bone, securing it with 6 screws. Two months later the plate was removed and, one month later, the patient returned to sport. This is the first case-report of a symptomatic compression of the brachiocephalic trunk by a posterior sternoclavicular dislocation. It is of high clinical significance because of the difficulty of an early diagnosis which, if delayed, could have lead to the death of the patient. Level of Evidence: 4 - Case Report.

Posterior sternoclavicular dislocations (P.S.C.D.) are also known as retrosternal, since the clavicle moves posteromedially, representing thus a risk of lesion or compression on important structures of the superior mediastinum: trachea, esophagus, brachial plexus, thoracic duct and great vessels.

We are talking about rare forms, which are mainly described as case reports in literature (1-25). Shimizu et al (24) described an interesting case of a lethal aortic arch injury caused by a rugby tackle.

The clinical importance of these reports is related to the risk of misdiagnosis, which determines a delay in treatment and may even have lethal consequences for the patient. The case report described in the present paper is about a retrosternal dislocation of the right clavicle, which caused a compression of the brachiocephalic trunk.

Up to now, literature has reported only one case of compression of the brachiocephalic trunk (in a fourteen-year-old boy), which, nevertheless, did not cause any anatomo-pathological damage nor clinical effects (25).

CASE REPORT

During a Regional Championship match, in an attempt to defend the ball, a 27-year-old Caucasian basketball player was elbowed by one of his opponents, in the region of the right sternoclavicular junction. Since he was complaining of persistent

Key words: Sternoclavicular, clavicle, dislocation, posterior, vessel, serious, brachiocephalic, trunk

Mailing address: Dr. Giacomo Placella,
Orthopedic and Traumatology Division,
Santa Maria della Misericordia Hospital,
University of Perugia,
06100 Perugia, Italy
Tel.: +39 075 5784107 Fax: + 39 075 5784107
e-mail: giacomo.placella@gmail.com

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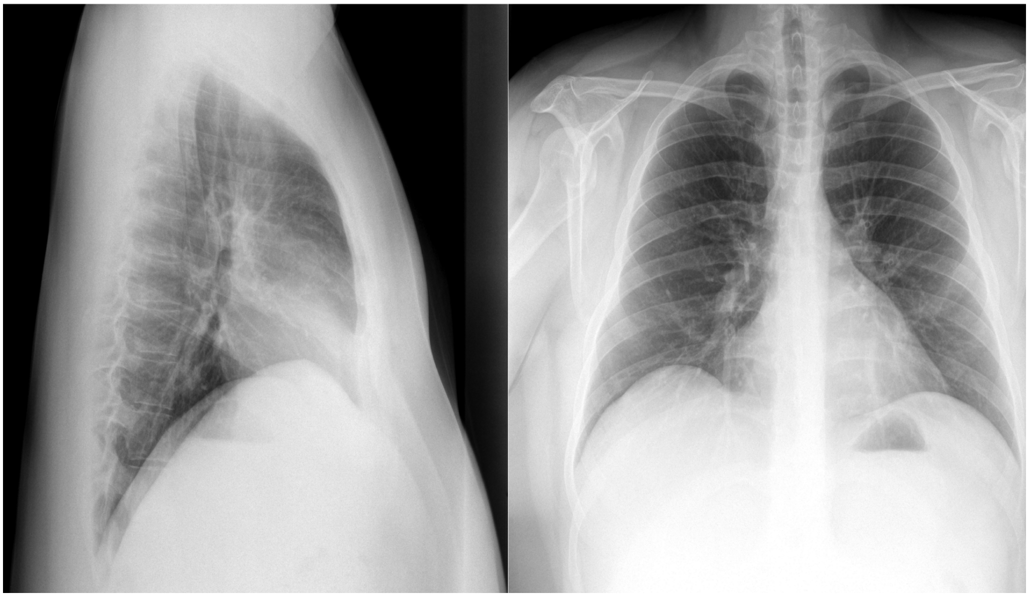

Fig. 1. *Chest x-ray of the patient at the time of the first access to the emergency room. The x-ray appears negative.*

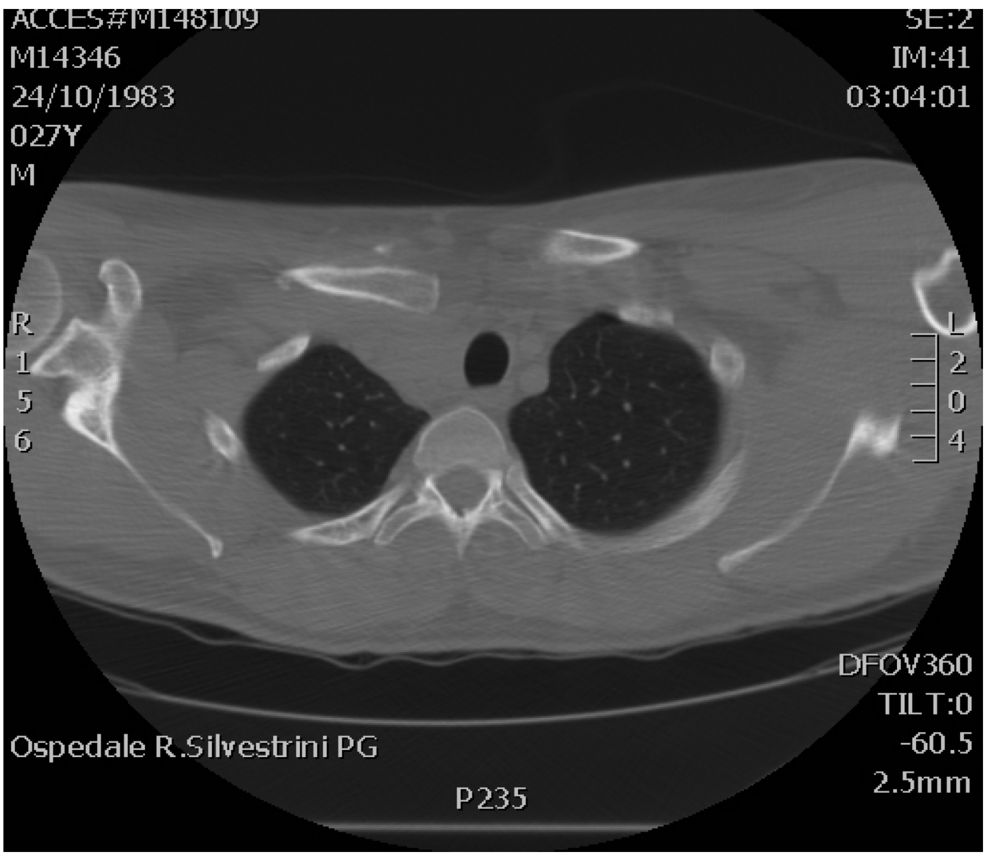

Fig. 2. *Chest CT-scan: the dislocation of the medial end of the right clavicle is clearly detectable.*

Fig. 3. *3D reconstruction chest CT-scan with contrast medium: right clavicle posterior dislocation with compression of the brachiocephalic trunk.*

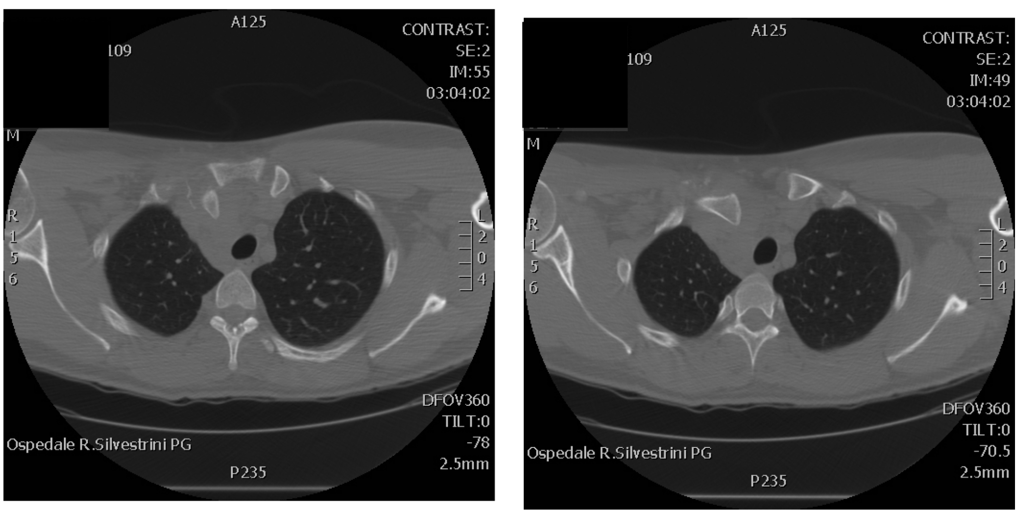

Fig. 4. ***A)*** *3D reconstruction chest CT-scan with contrast medium.* ***B)*** *Detail of the sternoclavicular joint.*

pain, he was taken to the emergency room of our Institution, where he underwent a chest X-ray. The X-ray was negative (Fig. 1).

Therefore, the man returned to normal daily training. After one month, during the warm-up before a match, although he had not undergone any trauma, he complained of shoulder pain and rigidity, associated with vertigo. During the match, he was hit in the sternoclavicular region. The impact caused him lipothymia and amnesia.

He was taken again to the emergency room, where he underwent some routine clinical tests: blood pressure 140/70; heart rate 99; arterial oxygen saturation 99%; hemoglobin 13.3 g/100 ml; HT 35.8%; MCV 76.2; MHC 25.3; neutrophils 90.14% in the leukocyte formula. The physical examination

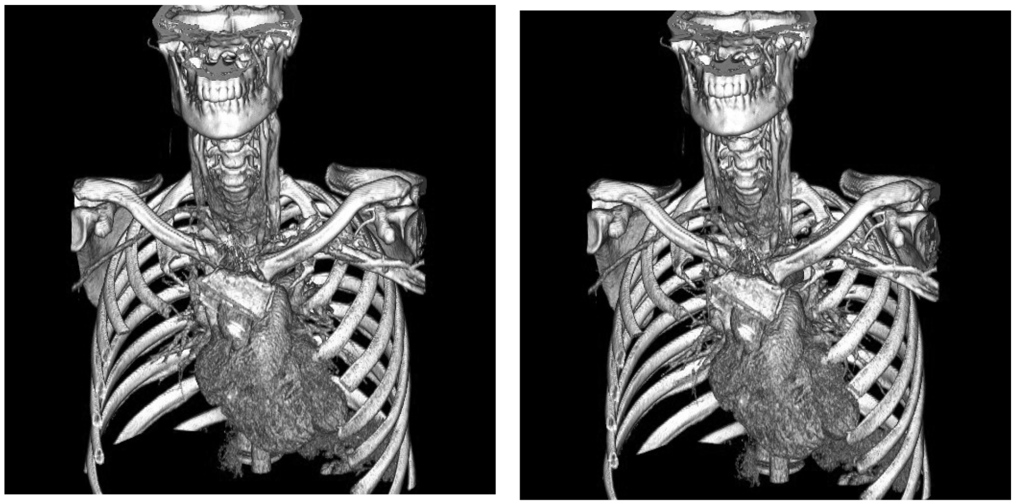

Fig. 5. *A portion of a 35 mm cross-carved plate (Synthes ®) in titanium was used. The figure shows how the plate was cut.*

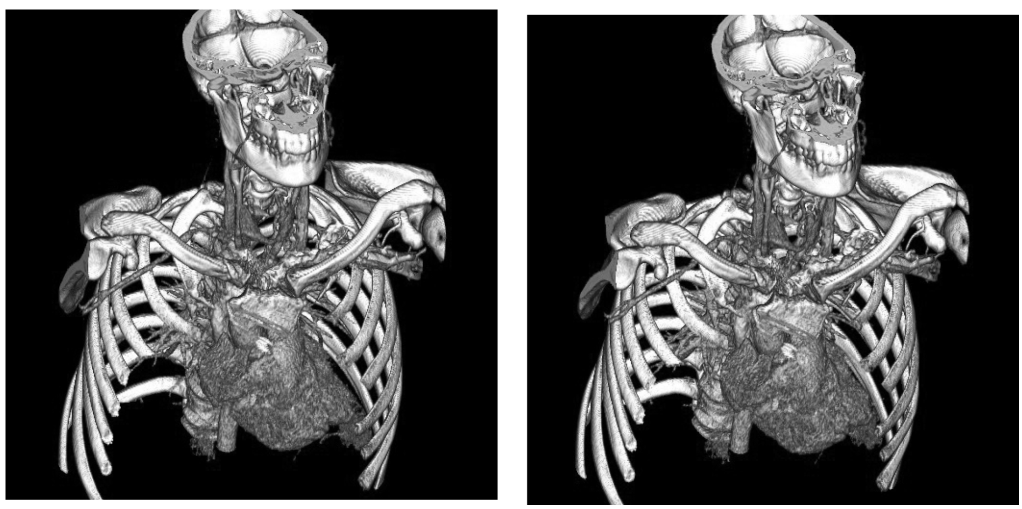

Fig. 6. *Surgical picture of the plate implantation.*

revealed a detectable pulse in the carotid arteries; whereas the right radial pulse was impalpable. Hence the patient was sent to the vascular surgeon for further clinical exams.

The patient underwent abdomen and thorax CT scan with and without contrast medium. The radiologist reported: "postero-inferior dislocation of the right clavicle, which determines the compression of the brachiocephalic trunk and contrast medium extravasation immediately before the origin of the subclavian artery, associated with opacization of the homolateral axillary artery only in the proximal tract" (Fig. 2-4).

A selective arteriography of the epiaortic trunks and a thoracic aortography were performed in emergency. The reports read: "Post-traumatic pseudo-aneurism of the brachiocephalic trunk and embolic obstruction between the right axillary and brachial arteries". The vascular surgeons removed the embolus by means of a Fogarty catheter and implanted a covered stent of 12 mm diameter in the brachiocephalic trunk. The final check showed the correct positioning of the stent.

During the same operation, through a median sternotomy extended to the xiphoid process, extensive fibrosis in correspondence of the jugulum, posteriorly to the right sterno-clavicular joint, was observed. After isolation of the thymus and the vascular structures, the mobilization and reduction of the medial head of the clavicle was done. In order to obtain good stabilization of the dislocation, we used a 35 mm cross-carved plate (Synthes ®) in titanium, opportunely modified in order for the plate to better adhere to the bone, and secured it with 6 screws (Fig. 5-6).

The sternotomy was closed by means of staples and an aspiration drain was positioned.

The surgical treatment was followed by immobilization in a sling and swathe immobilizer, 24 h/24 for 25 days. The patient also underwent a cautious passive mobilization of the shoulder (maximum abduction and flexion 90°) and active mobilization of the right elbow several times per day.

After 25 days, we removed the brace, and the patient started active mobilization of the shoulder, avoiding abducting and elevating it more than 90°.

At 2 months from the first operation, the plate was removed. During this second operation, we tested the stability of the plate, that was excellent. The sternoclavicular joint was also very stable. Immediately after the removal of the plate, the patient started an intense kinesitherapy program, with the aim of recovering complete R.O.M. of the operated shoulder and a balanced muscular strengthening of the shoulder complex. Recovery was complete after three weeks.

The patient, at one year from the first operation, is asymptomatic. One month after the removal of the plate, he returned to sport.

DISCUSSION

The sternoclavicular joint (SCJ) plays an important role within the shoulder girdle, because it is actually the only real joint that connects the upper arm to the trunk. Nevertheless, it is so little considered in literature that it is called “the forgotten joint”. It is not uncommon for this joint to present anatomic variations, both in different individuals and, in the same individual, in different life periods. This is why a posterior dislocation can cause various different types of complications and may lead to diagnostic errors. These diagnostic errors may be serious, since important structures of the mediastinum lie just behind this joint.

Sternoclavicular joint dislocations do not occur frequently: they represent 3% of all shoulder girdle traumas, and 1% of all the dislocations (26).

Among sternoclavicular dislocations, the anterior one has a much higher incidence than the posterior one, with a probability of 9:1 (16, 27-28).

Up to now, about 130 cases of the rare posterior sternoclavicular dislocations have been described in international literature, the first case being described by Sir Astley Cooper in 1824 (1, 5, 11, 14, 18, 20, 25).

Approximately 80% of these dislocations are due to violent impacts, such as car accidents (the so-called “seatbelt syndrome”), or sport whiplash injuries (rugby, football, horse-riding, etc.), and are caused by a posterolateral compression on the shoulder or an anteromedial impact on the clavicle (27). In some cases, posterior sternoclavicular dislocation is poorly symptomatic and does not induce any serious consequences for the patient. While, in other cases, serious and potentially lethal complications may well occur.

The serious complications include brachial plexus compression (13, 17) pneumothorax and respiratory distress (8, 20, 22-23), dysphagia and hoarseness (2, 8, 18-19) and, sometimes, death (10, 15). Some Authors report vascular damage secondary to P.S.C.D. Howard and Shafer (12) reported two cases of retrosternal clavicular dislocation with a compression of the subclavian artery and vein and a post-traumatic aneurism of the right subclavian artery, respectively. Gardner and Bidstrup (9) described a case of injury of the intrathoracic great vessels; Mirza et al (18) reported the complete obstruction of the brachiocephalic vein and impingement of the aorta; Kuzak et al (16) and Hoekzema et al (11) reported the compression of the brachiocephalic vein. A fatal compression of the brachiocephalic vein was described by Fenig et al (5). Shimizu et al (24) described an interesting case of a lethal aortic arch injury caused by a rugby tackle. Other articles about vascular injury caused by P.S.C.D, report the compression of the common carotid artery (14) and the subclavian artery (21). In the case report by Bensafi et al, the Authors describe a cardiac tamponade following the surgical fixation (1). As far as we know, the only article that mentions the compression of the right innominate artery, was recently published by Sykes et al (25). It is about the case of a 14-year-old boy, whose clavicular head just abutted the right innominate artery without compressing it and without symptomatic consequences.

The diagnosis of these lesions is often difficult, since the clinical picture can hide many other pathologies and sometimes plain X-rays are not resolving. Besides the routine antero-posterior view, it is also advisable to perform X-ray examination in lateral view and with a 40° sternum-centered head inclination (Wirth and Rockwood's serendipity view). The use of ultrasound is not essential, but it can be of help, in order to investigate possible complications, while MRI is useful in children and young adults, because it allows to distinguish a joint lesion from a physeal lesion. The gold standard for this type of lesion is the 3D CT-scan, which provides an excellent visualization of the sternoclavicular region and allows a precise diagnosis of the related lesions.

If there is a suspect of great vessel involvement such as the great epiaortic vessels or the great veins, angiography of the aorta should be performed,. Moreover, if there is the suspect of brachial plexus implication, a careful neurological examination is necessary.

Conservative treatment can be prescribed when there is no clinical evidence of joint instability after close reduction of the dislocation, or when pain is slight or moderate. It consists of analgesics, ice, shoulder immobilization from 2 to 6 weeks, on the basis of the degree of the dislocation and the pain.

Posterior dislocations are generally reduced under narcosis within 48 hours after the trauma, but it must be done immediately when there is evidence of compression of vital structures. On the contrary, surgical treatment is reserved for chronic instabilities or those dislocations that cannot be reduced in a different way (29).

This case report can be considered as unique, since it is the first one to describe the symptomatic compression of the brachiocephalic trunk exerted by a posterior sternoclavicular dislocation.

From a clinical point of view, it is an important case because it did mislead the physicians. Their error was due to the mild symptoms and the plain X-rays, that were apparently negative.

After injury, pain was so mild that the patient immediately returned to his sporting activity. However when he was hit again, as the dislocation was unstable, the clinical picture worsened. Indeed, a serious clinical condition developed which was life-threatening.

Surgical treatment was performed in emergency by the use of a 35 mm cross-carved plate (Synthes ®) in titanium, opportunely modified in order to make the plate adhere better to the bone, and secured it with 6 screws. We avoided using pins or wires. There are multiple reports of pin or wire fixation of the sternoclavicular joint having provoked serious complications, including death (22, 30-31, 33). In fact, none of the techniques proposed for P.S.C.D. stabilization have given a high number of excellent results, also because of the rarity of this injury. Plate fixation has been reported rarely, but with good results (6-7, 34-36). The necessity to perform osteosynthesis in emergency, and the lack of existing specific means of synthesis led us to choose this plate, which could well be debatable. However, the surgical treatment, that was a life-saving maneuver, obtained a good result.

The plate was removed after 2 months. This time span was decided upon as we felt that the plate had finished its function of giving temporary stability and we wanted to avoid a possible breakage due to its being rigid. Furthermore, we feared unduly slowing down the recovery of the complete range of motion of the patient's shoulder, especially when considering the fact that he is an athlete.

CONCLUSIONS

The importance of this case report lies in the fact that it is the first description in literature of a symptomatic compression of the brachiocephalic trunk caused by a posterior sternoclavicular dislocation. Its clinical significance is also associated with the difficulty in making the right diagnosis. This is why, when pain is reported in correspondence to the sternoclavicular joint following trauma, it is extremely important to carefully verify the absence of dislocations or fractures, which are not always visible in standard X-Ray images.

A late diagnosis may seriously endanger the patient's life.

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CASE SERIES

IS THE ACHILLES TENDINOPATHY CAUSED BY THE TENSION OF ACHILLES-CALCANEAL-PLANTAR SYSTEM?

A. FOLLIERO[1] and M. G. MINICELLI[2]

[1]Fisioeuropa, Rome; [2]Department of Orthopedics and Traumatology, "S. Pietro Hospital", Rome, Italy

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The aim of our study was to detect if there is a correlation between non insertional Achilles tendinopathy and the typical foot structure. We found a correlation between Achilles tendinopathy and cavus foot, this led us to think that the Achilles tendinopathy could be caused by the tension of Achilles-calcaneal-plantar system wherefore we decided to treat these patients with the detension of Achilles-calcaneal-plantar system obtained by a heel lift. All patients were evaluated with a clinical and podoscopic examination of foot and ankle, Visual analogue scale (VAS) and ultrasound exam. All patients with Achilles tendinopathy had a cavus foot. The ultrasound exam showed two different aspects of the tendon with and without degenerative changes. In the patients treated with the detension of Achilleo-calcaneal-plantar system, at a mean follow up of 3 months the VAS scale showed a excellent and good score in all patients with moderate and severe clinical symptoms. The satisfactory clinical results obtained by the detension of Achilles-calcaneal-plantar system lead us to believe this Achilles tendinopathy a possible biomechanics disease. Level of Evidence: 4 - Case Series

The Achilles tendinopathy is a clinical syndrome characterized by a combination of pain, swelling and impaired performance. The incidence in the adult population is estimated to be 2.35 per 1,000 persons per year (1). Despite its considerable incidence, the aetiology is unknown and the result of an optimal treatment is unclear (2-3). The aim of this study is to evaluate the foot structure of patients with non insertional Achilles tendinopathy and the possible role of the Achilles-calcaneal-plantar system detension in the treatment of this disease.

MATERIALS AND METHODS

Between January 2007 and November 2012, 3873 nonathletic patients with foot injuries were included in this case-series study. The patients were aged from 14 to 80 years. Among these, we found 380 patients with non insertional Achilles tendinopathy. In this group there was a total of 150 women and 230 men with a mean age of 50 years (range: 30 to 70). The diagnosis of Achilles tendinopathy was established on clinical examination that included self subjective reported pain, palpation test to feel the tendon thickening and/or the crepitus in the whole length of the tendon and impaired gait. The pain levels were assessed using the Visual Analogue Scale (VAS) (4). The severe and moderate pain corresponded to 5 or more on the 10 point VAS. The 380 patients with non insertional Achilles tendinopathy was examined by ultrasound scan from the musculotendinous junction to its insertion on the calcaneus in both the

Key words: Achilles tendinopathy, Achilles-calcaneal-plantar system, Achilles tendon

Mailing address: Dr. Maria Grazia Minicelli,
Department of Orthopedics and Traumatology,
"S. Pietro Hospital",
V. Cassia 600,
00189 Rome, Italy
Tel.: +39 329 2275748 Fax: +39 06 5910802/802
e-mail: dottoressaminicelli@gmail.com

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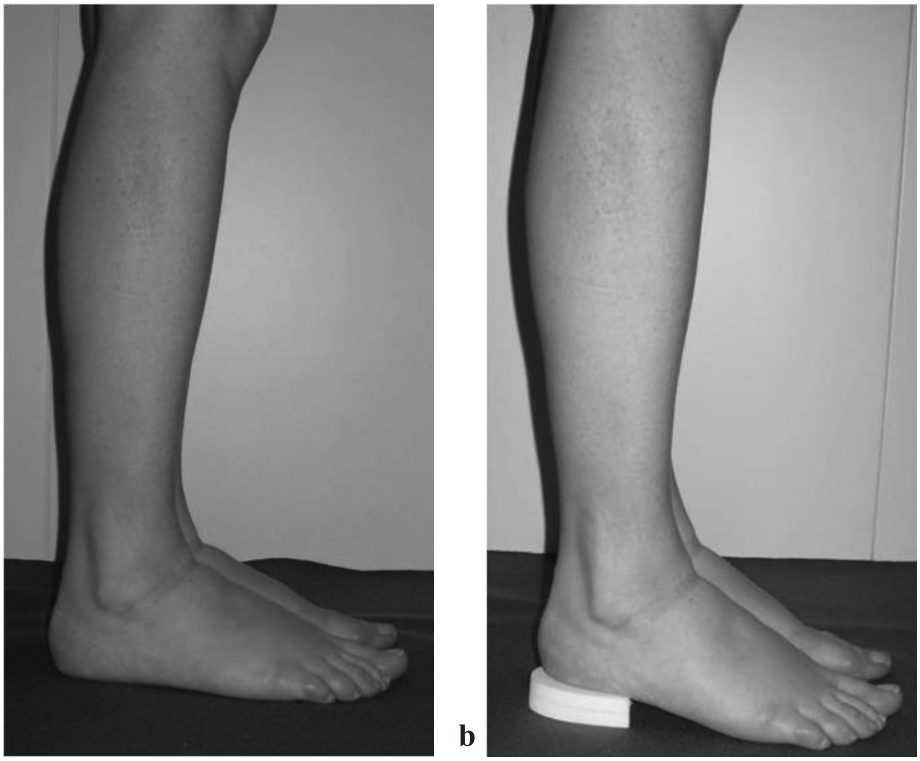


Fig.1. *A) The cavus feet without the heel lift.* ***B****) The cavus feet with the heel lift that caused the detension of Achilles-calcaneal-plantar system.*

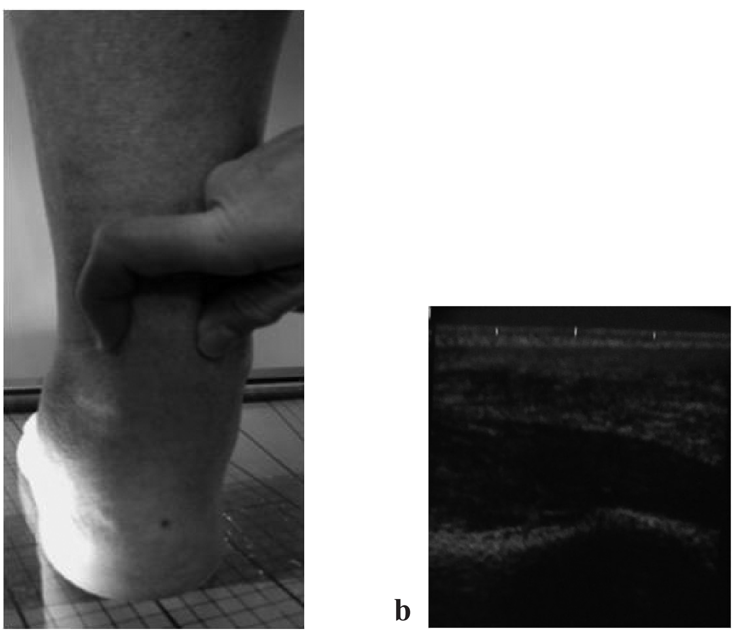


Fig. 2. *A) Achilles tendon with clinical peritendinous edema and thickening in symptomatic patient.* ***B****) Ultrasound exam of Achilles tendon with peritendinous edema and thickening in symptomatic patient.*

a

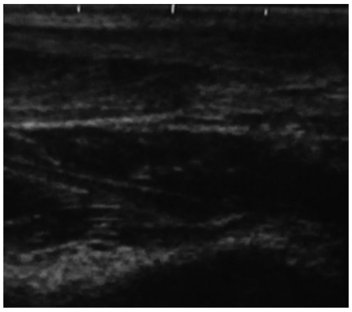
b


Fig. 3. *A) Achilles tendon with degenerative fibres and nodular thickening in mid body tendon.* ***B****) Ultrasound exam of Achilles tendon with degenerative fibres and nodular thickening in mid body tendon*

longitudinal and transverse planes. The foot structure was investigated by the podoscopic exam. We treated the male with a heel lift that was 10% of the length of the shoe sole and the female with a heel lift of 4 centrimetres to obtain the Achilles-calcaneal-plantar system distension (5-6) (Fig. 1 A and B).

RESULTS

All patients with Achilles tendinopathy had a cavus foot. By the ultrasound scan the edema in the peritendinous tissue with normal tendon fibres was found on average in 83% of patients. The hypoechoic changes, calcifications, defects and disorganizations of collagen fibres were found on average in 7% of patients. In the most of patients with severe and moderate pain at ultrasound scan the tendon fibres structure was normal with peritendineus edema and thickening in the whole length of the tendon (Fig. 2 A and B). In most patients with any or mild pain and with thickening in the mid body of the Achilles tendon we found degenerative changes of the fibres (Fig. 3 A and B). At 3 months from the treatment with the heel lift, all patients with mild pain were asymptomatic, instead all patients with moderate and severe pain had pain relief (from 1 to 5 point VAS). At 6 months from treatment in all patients with mid body nodular thickening of the tendon, the thickening was clinically reduced. We did not observe any case of tendon rupture.

DISCUSSION

We observed in the non insertional Achilles tendinopathy two morphological aspects of the tendon: the peritendinous edema with a normal collagen fibres and the degenerative changes of the collagen. These different morphostructural aspects do not always coexist. In our experience, the moderate and severe pain was peculiar of the morphostructural aspect of the edema peritendinous with normal collagen fibres, instead the asymptomatic clinical status was common in patients with a degenerative tendon and nodular swelling. In this study, all patients with Achilles tendinopathy had a cavus foot. According to R. Arandes, A. Viladot (7) and G. Pisani (8) we believe that the anatomical variant of cavus foot occurs frequently in the population and that this variant is characterized by a short Achilles tendon. We suppose that this peculiarity leads to continual tension of the Achilles-calcaneal-plantar system with possible tendinopathy. In our study, the treatment with heel lift that leads to detension of Achilles-calcaneal-plantar system causes at a short follow up, excellent clinical reduction of pain and edema in patients with non insertional Achilles tendinopathy. In conclusion, we believe that the Achilles tendinopathy can be considered a biomechanical disease and the detension of Achilles-calcaneal-system the main treatment of this disease, with physical therapy as adjuvant therapy.

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CASE SERIES

THE EFFECT OF KINESIO TAPE ON ACTIVE WRIST RANGE OF MOTION IN CHILDREN WITH CEREBRAL PALSY: A PILOT STUDY

A. DEMIREL and V. TUNAY BAYRAKCI

Department of Physiotherapy and Rehabilitation, Faculty of Health Sciences, Hacettepe University, Ankara, Turkey

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The aim of the study was to determine active range of motion of the wrist after kinesiotaping of the wrist exstensor muscles in children with cerebal palsy (CP). Fifteen children aged between 6 and 18 years participated in the study. Inclusion criteria were: to have CP diagnosis (except for the dyskinetic form), to be level 1 or 2 of the manual ability classification system (MACS), to have mild spasticity according to to the Modified Ashworth Scale (MAS), to not have had a Botox – A application in the past year, to have dynamic or functional deformity. Before taping, wrist extension, radial and ulnar deviation movements were measured actively with a goniometer. While a non- heavy plastic ball was grasped by children with wrist at full extension and shoulder in the 90° flexion position, wrist extension was measured. Kinesiotape was applied on wrist extensor muscles with according to the functional correction technique. After kinesio tape application, all measurements were repeated. Statistically significant differences were found in wrist extension, radial, ulnar deviation active range of motion and wrist extension range of motion while functional ball grasping improved after taping ($p<0.05$). While kinesio taping increases wrist movements in children with CP, it also contributes to the functional grasping of these children. Based on these positive results kinesio taping could be used in the treatment programs of children with CP. Level of Evidence: 4 - Case Series

Cerebral Palsy (CP) is the most common cause of severe physical disability in childhood and is defined as a static perinatal brain injury (1-2). The worldwide prevalence and incidence of CP are not defintely known (3). The overall reported prevalence in children aged 3-10 years is 2.4 per 1000 babies born at term and is mostly associated with single hemisphere injury (4-5).

Imbalance between agonist and antagonist muscles affects the posture of the upper extremity. The extent of impaired movements includes shoulder internal rotation, elbow flexion, forehand pronation, wrist and finger flexion and thumb-in-palm deformity (6). Park et al. observed 234 children with CP and found shoulder abduction and elbow extension limitation, forearm pronation deformity, finger flexion, swan neck, intrinsic minus and plus deformity, finger and wrist flexion deformity and thumb-in palm (7). Various combinations of these impairments cause difficulties in reaching, grasping, pointing and other daily life activities (8). During reaching, grasping and manuplation tasks, deficiency is seen in children with CP due to proximal and distal instability, muscle weakness, sensorial loss, spasticity, tigthness/shortness of muscles (9-10). Secondary contractures and joint deformities reduce

Key words: kinesio tape, cerebral palsy, range of motion

Mailing address: Dr. Aynur Demirel
Department of Physiotherapy and Rehabilitation,
Faculty of Health Sciences,
Hacettepe University, 06100Ankara, Turkey
Tel.: +90 312 305 2525-139
Fax: +90 312 305 2054
e-mail: aynurdemirel629@hotmail.com

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the range of motion (11). The flexor carpi ulnaris (FCU) muscle is two times more rigid in children with cerebral palsy as compared to healthy peers (12). It causes stiffness, movement disorders and mal-posture of the hand. Wrist flexion movement is more dominant in relation to the increased degree of flexion causing extension of this joint to be difficult (13**).** Wrist flexion deformities has three subgroups; static, dynamic and functional deformities. In the static deformities, the wrist has a greater than 45 degrees of flexion contracture and surgical techniques such as arthrodesis is needed to correct the hand posture. In the dynamic deformities, the wrist has an extension movement - although not full range - and contracture is not seen. Tendon transfers could be used to improve the hand function. In the functional deformities, the wrist has full range of active extension but during handling objects, the wrist flexor muscle could be active (2).

Children with CP may undergo various treatment methods and interventions including neurodeveolopmental approaches, surgical techniques, occupational and physical therapy. Muscle or tendon lenghtening and transfer techniques have been shown to enhance hand function (11). Botulinum toxin-A injection is used to reduce muscle tone in the spastic hand of CP patients (14). Orthotic devices are used to support proximal stability for grasping and facilitating functional use of the hand and also for preventing the formation of deformities (15).

Kinesio tape is a relatively new method generally used in rehabilitation programs to treat upper arm or hand pain. Besides pain relief, kinesio tape, when applied properly, can theoretically help good postural alignment and relax an overused muscle. Correctional procedures deal with positioning, aiming to maintain balance within the muscles and increase their functional level (16). It achieves a nearly full range of motion with different pulling forces. By lifting the fascia and soft tissue, it creates a realignment of the fascia and achieves normal muscle function, improving blood circulation, strength of muscle force and endurance (17). Yasukawa et al. has shown that kinesiotape application assists reaching, grasping-relasing and manupulation in the acute pediatric rehabilitation setting (18). Kinesiotape is also used for preventing stroke-related shoulder subluxation by supporting the trunk and shoulder muscles (19). Lee et al. found increase hand grip strenght in patient with asymetrical tonic neck reflex after application of kinesio tape on the flexor muscles of the dominant hand (20).

Range of motion is an important component of body structure and function (21). Only a few articles have focused on impaired hand function and range of motion in cerebral palsy. Based on the gap in the literature, we had two hypotheses: 1) kinesio taping could change the range of motion of the wrist 2) kinesio taping could improve the mal-posture of the hand by supporting wrist extension and reducing flexor muscle dominance. Therefore the purpose of this study was to determine the active range of motion of wrist exstensor muscles after kinesio taping in children with CP.

MATERIALS AND METHODS

Participants

Fifteen children diagnosed with CP (10 boys, 5 girls; mean age 11.2±3.14 years; 8 hemiplegic CP, 7 diplegic CP) were included in the study. Subjects with CP were chosen according to their grasping and spasticity level. The children enrolled in this study had dynamic or functional deformity. Inclusion criteria were: having an un-aided functional sitting ability and independent trunk control, being level I or II of Manual Ability Classification System (MACS), having mild spasticity or having normal tonus (be 1 or 1+ level of Modified Asworth Scale). The MACS is a five level tool that classifies the usage level of the children aged between 4 to 18 years in daily life. At level I, handling the objects is easy and the grasping quality is good, at level II grasping most objects is still possible but alternative ways may be chosen and grasping quality and speed is reduced compared to level I. At level III grasping is still possible but modification of the activities and preparation is needed. At level IV a limited grasping of objects is possible and continuous support is needed. At level V handling is impossible and total assistance is needed (22). Subjects were excluded if they had static deformity, abnormal visual and hearing capacity, impaired intelligence or mental retardation which would affect the understanding of the test positions, thumb-in palm deformity, additional hand injuries (fractures, orthopedic injuries, burns, etc.). None of the subjects had undergone Botox-A injections or operations to the upper extremity. All of the children with CP continued a physiotherapy and rehabilitation program.

All subjects and their parents had read and signed an informed consent form before the evaluations.

Procedure

Two parameters were investigated in this study; wrist range of movement and wrist extension range of functional motion while grasping a ball. Wrist extension, radial and ulnar deviation movements were measured actively with a goniometer. While a non- heavy plastic ball was grasped by children with their wrist at full extension and shoulder in a 90° flexion position, wrist extension was measured (Fig. 1).

During the test, all the children were asked to do movements carefully. All measurements were done before and after taping .

Kinesio taping application (wrist extension assist taping)

Kinesio taping, created by Kenzo Kase in 1976, uses taping which is thin, elastic and can be stretched up to 120%~140% of its original length, it has a wave like grain compared with the rigid taping used by athletes. In this study, kinesio tape was applied to the wrist extensor muscles using the functional correction technique from dorsum of hand to lateral epicondyle (Fig. 1). Before starting the test, the children wore kinesio tape for 45 minutes to assure the maximum effect.

Statistical analysis

Statistical analyses were performed using the SPSS software version 15. The variables were investigated using visual (histograms, probability plots) and analytical methods (Kolmogorov-Simirnov/ Shapiro Wilk's test) to determine whether or not they were normally distributed. Descriptive analyses were presented using medians and interquartile range (IQR) for the non-normally distributed and ordinal variables. Since the wrist range of motion measurements were not normally distributed; nonparametric tests were conducted to compare these parameters, as well as to compare the ordinal variables. The Wilcoxon test was used to compare the change in the wrist range of motion degrees following taping. A p- value of less than 0.05 was considered to show a statistically significant result.

RESULTS

Qualitative results

After the application of kinesio tape, the whole posture of the hand was changed. It was significant when grasping the ball, the hand tends to deviate radially and wrist flexion decreases. When asked to reach for and lift the ball, not only wrist joint extension quality was remarkably increased, but proximal joints of the upper extremity also showed a better posture compared to the results obtained in the non-taped trial.

Quantitative Results

Table I shows the data relative to the changes in the subjects' wrist range of motion. Wrist extension range of motion increased after taping (p=0.008). Wrist extension range of motion while grasping a ball increased after taping (p=0.008) and the increased extension was degrees greater than when not grasping the ball. A significant outcome of the results in children with CP after taping was an increased radial deviation range of motion and a decreased ulnar deviation range of motion. The changes of range of motion were significant (p=0.001) and are shown in Fig. 2.

DISCUSSION

Treatment techniques of impaired hand movement in children with cerebral palsy vary and focus on improving functional outcomes. Kinesio taping is a new method for improving conditions of the upper extremity. Although evidence-based studies show

Table I. *Descriptive statistic of range of motion and comparisons*

	Before taping					After taping					
	Min	Max	25th	50th	75th	Min	Max	25th	50th	75th	p
Extension	-35	49	-3	20	35	21	48	27	30	38	.008*
Grasping ball extension	-58	30	-10	12	21	-29	54	24	32	38	.003*
Radial deviation	10	18	11	12	15	12	22	14	15	20	.001*
Ulnar deviation	24	38	28	33	35	15	33	22	23	25	.001*

Fig.1. *Grasping the ball before and after taping*

that kinesio taping improves functional usage of the upper extremity there is still a gap in the literature about changes in the range of motion. The main aim of this study was to gain further insight into the efficacy of the kinesio taping method by determining the wrist range of motion in children with CP.

The degree of impairment of the hand in children with CP is determined using various classification scales such as the Manual Ability Classification System (MACS), the Melbourne Assessment of Unilateral Upper Limb Function (MELBOURNE), the Quality of Upper Extremity Skills Test (QUEST), the Assisting Hand Assessment (AHA), the Shriners Hospital for Children Upper Extremity Evaluation (SHUEE), the Modified House Functional Classification System (MHC) and the Upper Extremity Rating Scale (UERS). In therapy or treatment programs, using score sheets could be the best tool for determining changes or improvements in hand function. However all of these easy to use scales evaluate hand function between angles, not just at a set point, hence the goniometer was an easy to use, available tool for the assessment of the immediate effects of taping on wrist active range of motion in this study.

While grasping the ball, not only did wrist extension improve and increase but elbow extension was also remarkably improved. Muscle releasing, lengthening, rerouting techniques and target muscles differ for static, dynamic and functional deformities. For dynamic deformities of the hand, the effective surgical treatment would involve the wrist flexor to the radial wrist extensor; in functional deformities of the hand, the effective treatment is lengthening the spastic flexors while transferring any muscles to the wrist extensor is not needed. In both surgical techniques, the primary aim is to increase the extension of the wrist (2). It is obvious that the effect of kinesio tape is the same with wrist extension assisted by taping so it could be used in both pre-operative and post-operative treatment in pediatric rehabilitation settings.

Botox-A reduces spasticity, increases joint mobility and lets children perform upper extremity movements comfortably and activities in daily life with less energy. A study showed that Botox-A administration has positive effects on wrist extension by reducing wrist flexor tone for at least 9 months following the injection while the children continue occupational and physical therapy (21). Combined therapy modalities of Neuromuscular Electric Stimulation (NMES) and Dynamic bracing reduce spasticity by strengthening the antagonist muscle of the spastic muscle and lengthening the shortened muscles (23). This study shows that kinesio tape effects the wrist extensor muscles, the antagonist muscle of the spastic muscle, increasing range of motion by lifting the fascia.

Studies show that the transfer of FCU muscle to extensor carpi radialis brevis (ECRB) muscle exist in late onset deformities such as extension, supination and recurrent flexion deformity. Literature reports that post-operative deformity occurs in 13% to 69 % patients who have these tendon transfers (24-25). According to one study 82 % of these patients develop post-operative late deformity when performed before age of thirteen (26). Kinesio tape may be an effective approach for children with impairments and who have not yet reached skeletal maturity.

Fascia is known as a key component between body structures, force transmission and directly affecting muscle strength. Fascial connections remain the same and keep the original muscle torque capacity after FCU transfer or tenotomy. Due to fascial connections, FCU tenotomy alone cannot prevent recurrent flexion deformity (27). Kinesio tape decreased ulnar deviation range of motion and increased radial deviation range of motion by effecting the fascia directly. A study found that conservative therapy and functional taping gives better results than physical therapy alone (28).

Current treatment modalities such as surgery, Botox-A, NMES and neurodevelopmental approaches are not always suitable and effective. Kinesio tape could be tried as a new option in the pediatric rehabilitation setting.

One limitation of the study was the inadequate number of participants to generalize the effect of kinesio tape according to CP classification. Further studies will focus on different age groups, types of CP and other range of motion measurements of the upper extremity. The use of kinesio tape in children with static deformity is not effective, therefore our results only indicate outcomes for children with dynamic and functional deformity.

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NARRATIVE REVIEW

ARTICULAR CARTILAGE MORPHOLOGY AND BIOMECHANICS

D. DEPONTI[1], M. DOMENICUCCI[1] and G. M. PERETTI[1,2]

[1]IRCCS Istituto Ortopedico Galeazzi, Milan; [2]Department of Biomedical Sciences for Health, University of Milan, Milan, Italy

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Articular cartilage is a tissue that is deeply involved in the biomechanics of the knee joint. It is characterized by an interesting and specific architecture where few specialized cells, the chondrocytes, are able to produce structural proteins, such as glycosaminoglycans and collagen II, in response to biological and mechanical stimuli. These macromolecules assume different orientations in the extracellular matrix in order to mediate the specific mechanical responses that are required in the different zones of the chondral tissue. In particular, collagen fibers participate in the response to tensional and shear forces, while glycosaminoglycans mediate the response to compression forces. When degeneration or extensive injury occurs to the cartilage, this tissue is not able to spontaneously heal; so the specialized architecture is permanently lost and the affected area is not able to mediate the physiological mechanical functions of the knee joint. Several projects have been developed with the purpose of regenerating cartilage, by using growth factors, cell therapy or biomaterials. However, all these approaches can be successfully applied only once one has profound knowledge of the morpho-functional aspects of articular cartilage. The aim of this article is to achieve this by summarizing the morphological, structural and functional characteristics of this tissue, highlighting the aspects that are fundamental to understand the biology of chondral tissue. Level of Evidence: 5 - Narrative Review

ARTICULAR CARTILAGE STRUCTURE AND COMPOSITION

Articular cartilage is an opalescent white tissue that covers the articular surfaces of diarthrosis. This tissue is made up of an abundant extracellular matrix that is composed of a higher water content, proteoglycans and collagen. The constant presence and renewal of these matrix components is sustained by the synthetic activity of a population of specialized cells that are called chondrocytes.

A different structure and composition is observed throughout the different layers, from the subchondral to the superficial one, in particular in regards to cellular size and volume, collagen fiber orientation, proteoglycans and water content. Based on this organization, four distinct zones can be observed (Fig. 1 and 2): the *superficial tangential zone* (Fig. 1 and Fig. 2B), the *intermediate zone*, the *deep zone* (Fig. 2C) and the *calcified cartilaginous zone* (1-3). A thin tide-mark can be seen between the deep layer and the calcified one; this tide-mark is also well recognizable in the histological preparations of articular cartilage. In the superficial tangential zone, the collagen fibers have a parallel orientation with respect to the articular surface and few cells are present with the same parallel orientation; moreover, this zone is characterized by a reduced water and proteoglycan content, the lowest one in this tissue. The intermediate zone contains larger collagen

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Mailing address: Prof. Giuseppe M. Peretti,
Head of the Regenerative and Reconstructive Orthopedic Unit,
IRCCS Istituto Ortopedico Galeazzi,
Via R. Galeazzi 4, 20161 Milan, Italy
Tel.: +39 02 66214930 - +39 02 66214735 Fax: +39 02 66214736
e-mail: gperetti@iol.it giuseppe.peretti@unimi.it

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fibers and is organized in an amorphous network, the chondrocytes have a spheroidal shape and greater synthetic activity. In the deep zone, collagen fibers are perpendicularly oriented to the superficial layer, and the matrix is characterized by a lower amount of water and a maximum content of proteoglycans; the chondrocytes show a higher metabolic activity and are grouped in columns formed by 4-8 cells that are perpendicular to the superficial layer (4). The calcified zone is 1 millimeter deep or less and it is a transition structure between the cartilage and the subchondral bone: in this region, there are few chondrocytes and they are defined as being hypertrophic, due to their greater size, and they are surrounded by a bone-like matrix.

The extracellular matrix shows regional differences depending also on the interaction with the chondrocytes: in fact, it is possible to distinguish a pericellular, territorial or inter-territorial matrix depending on its proximity to the chondrocytes; these regions differ for their collagen and proteoglycan content and for fiber size and orientation. The pericellular matrix is a thin layer adjacent to the chondrocyte cell membrane which completely surrounds them; it does not contain collagen fibers but proteoglycans and other components (5-6). The territorial matrix surrounds the pericellular matrix and it is characterized by thin collagen fibrils that are organized into a different fibrillar network with respect to the inter-territorial matrix. The inter-territorial matrix is the principal component of the cartilaginous matrix; it contains larger collagen fibers and has the greatest portion of proteoglycans present in the cartilage.

Chondrocytes

Chondrocytes are specialized cells that are able to synthesize and secrete the specific components of the cartilaginous matrix. They derive from mesenchymal progenitors that differentiate into chondrocytes during the skeletal morphogenesis. In adult cartilage, they represent less than 10% of total tissue but their synthetic activity is sufficient to maintain the composition of the cartilaginous matrix constant and stable. In fact, these cells have an active metabolism and they are able to activate different synthetic pathways (inducing an anabolic or a catabolic process) upon stimulation from the surrounding environment, such as stimuli from growth factors, interleukins, pharmacological molecules, matrix molecules, mechanical stress and hydrostatic pressure changes. In particular, some molecules, such as interleukin-2, induce catabolic activity that leads to degradation of the cartilaginous matrix instead of an anabolic activity that would enhance its preservation: typically these molecules are released upon activation by the immune system and the catabolic effect they induce on cartilage is the basic mechanism leading to the development of osteoarthritis (7-8). An alternative interesting population has been found in the superficial zone (SZ) of articular cartilage, as the one responsible for the appositional growth of the tissue. This population of SZ chondrocytes share some characteristics of mesenchymal progenitor cells, as demonstrated by the high proliferative rate that is typical of pre-chondroblastic cells during early chondrogenesis. This high proliferative potential seems to be related to beta-catenin expression (9-11).

Collagen

Collagen molecules represent the main components of the cartilaginous matrix. Indeed, the main isoform in this tissue is collagen II but there is also a small percentage of other isoforms, such as collagen V, VI, IX, X and XI. All the collagen isoforms share the same capacity to form a triple helix structure in the extracellular space. These collagen fibers mediate important mechanical functions, such as the resistance to tensional and share forces, and the immobilization of proteoglycans within the matrix. Articular cartilage collagen is made up of fibers of a reduced diameter compared to the collagen fibers present in tendons and bones; this is due to the considerable presence of proteoglycans in this tissue. The collagen molecules interact with each other through intra- and inter-molecular bonds, forming a narrow tridimensional network that mainly mediates tensional resistance to the cartilaginous tissue (12).

Proteoglycans

Proteoglycans are molecules formed by a central protein core which covalently binds to polysaccharidic chains called glycosaminoglycans that are formed by long chains of disaccharidic units (25-30 repetitions for each chain), such as chondroitin

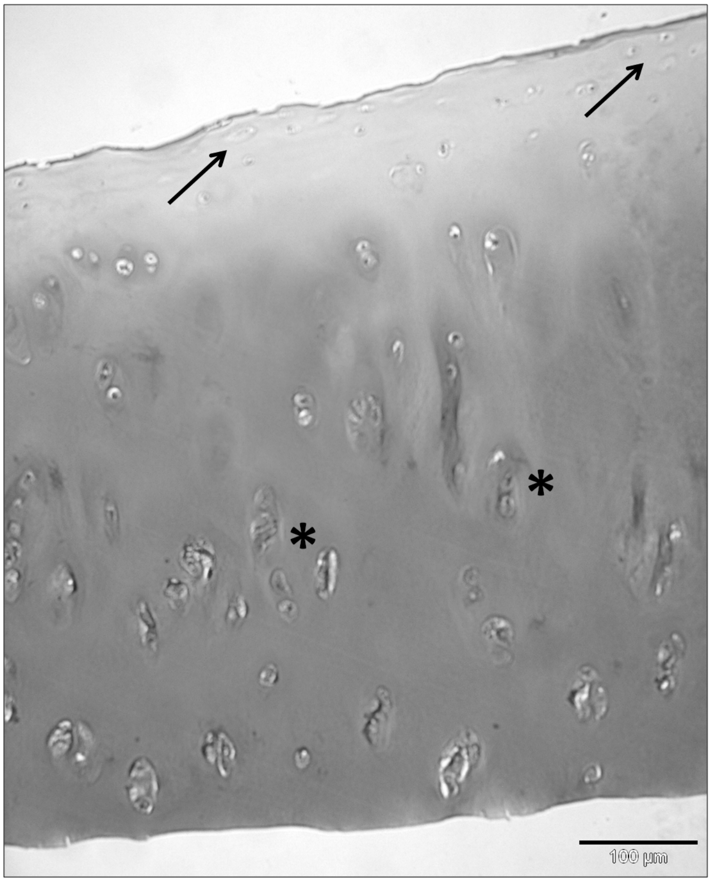

Fig. 1. *Human articular cartilage, SAFRANIN-O staining, scale bar 100 μm. Arrows indicate the superficial tangential zone, characterized by cells having a parallel orientation in respect to the articular surface. Asterisks indicate the deep zone, characterized by cells having a column-like distribution with a perpendicular orientation to the superficial layer.*

sulphate, keratan sulphate and dermatan sulphate (13). Chondroitin sulphate is the most represented in the articular cartilage. Glycosaminoglycans contain several carboxyl (COOH) and sulphate (SO_4) groups that acquire negative charges in aqueous solution attracting positive ions and water by osmosis.

The major proteoglycan in the articular cartilage is the aggrecan, characterized by a big protein core to which as many as 100 chondroitin and 50 keratan sulpahtes are bound; the N-terminal portion, one of the globular domains, binds non covalently the hyaluronic acid, forming aggregates that are known as proteoglycan aggregates; this bond is so closely linked that is almost irreversible, unless a proteolytic approach is applied. Each hyaluronic acid molecule can bind different aggrecan molecules forming large aggregates (14); the size of these aggregates decreases with age and the degeneration of the cartilaginous tissue. There are also other proteoglycan molecules that are less represented, such as decorin and byglican, that are smaller than the aggrecan: decorin contains only one dermatan sulphate chain, while byglican contains two dermatan sulphate chains. Decorin is distributed on the surface of collagen fibrils where it regulates fibrillogenesis and fibril diameter.

The proteoglycans distribution in the cartilaginous matrix is not constant but it increases from the superficial region to the transitional and deep one and it is more represented in the pericellular matrix compared to the surrounding one.

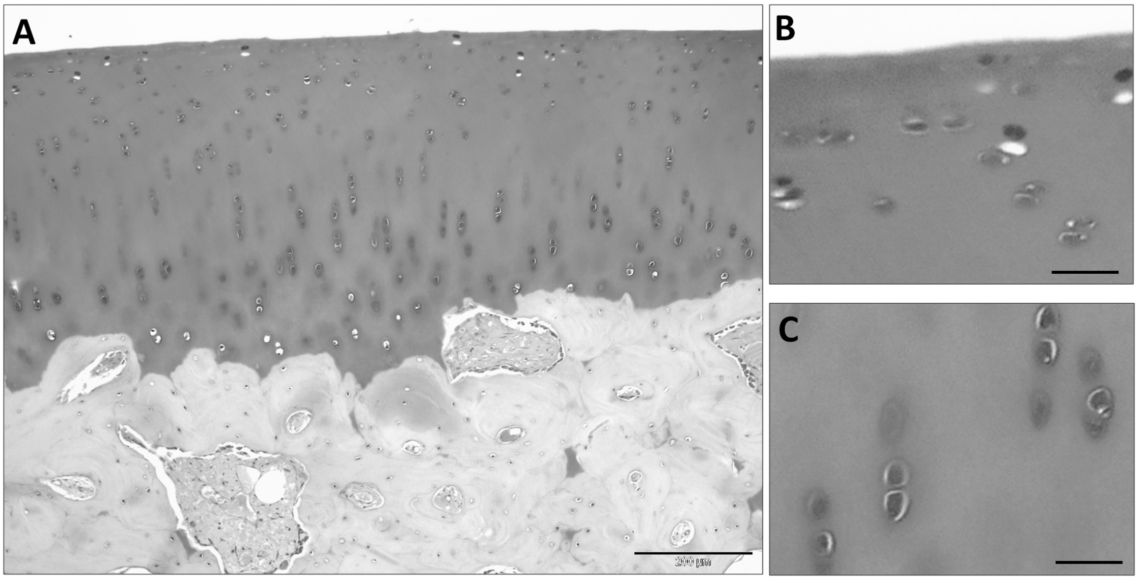

Fig. 2. *Swine articular cartilage, SAFRANIN-O staining.* ***A)*** *Scale bar 200 µm. Overview of the osteo-chondral tissue: a strong positivity for GAGs is observed in the chondral phase.* ***B)*** *Scale bar 50 µm. Superficial tangential zone of the cartilage: cells have a parallel orientation with respect to the articular surface.* ***C)*** *Scale bar 50 µm. Deep zone: cells are grouped in columns with a perpendicular orientation to the superficial layer.*

ARTICULAR CARTILAGE MECHANICS

Articular cartilage has the function of bearing statically applied loads, in a cyclic and repetitive way; as a consequence, the macromolecules that are present, such as collagen and proteoglycans, have to be organized in a solid matrix that can resist such loads. Eighty percent of cartilage matrix is made up of water and the remaining 20% is the solid fraction; due to this particular composition, articular cartilage acts as a biphasic model where the solid and liquid phases cooperate to mediate the specific mechanical functions required of this tissue. The solid phase is made up of collagen and proteoglycans whose negative charges attract positive ions which in turn attract water by osmosis. Water is then accumulated in the extracellular matrix thanks to the reduced permeability. The hydrostatic pressure that is generated in presence of compressive forces mediates the load transfer from the superficial to the deep layer in an homogeneous way, protecting the solid component of the matrix and resulting in a minimal involvement of the solid phase in the biomechanical response (15). Collagen fibers are fundamental for their involvement in shear force stress, thanks to their resistance to tension and torsion. In particular, the fibers of the intermediate zone, that are apparently oriented in a random way, allow cartilage to deform without any liquid discharge. Consequently, when articular cartilage is subjected to shear forces, the solid phase is directly involved in this mechanical stress leading to degeneration of this component. However, articular cartilage is able to prevent this phenomenon thanks to the tissue lubrication that reduces the superficial tensional stress.

There is no innervation, immune cells or immunoglobulins in the articular cartilage, thus the chondrocytes are isolated from all signals coming from other body compartments. However, these cells possess a high sensitivity to biomechanical stresses coming from the surrounding environment; they are able to activate specific responses to the signals perceived by the cell membrane. These signals are probably perceived and transduced by membrane integrins leading to the activation of intracellular pathways and, finally, to the modulation of cell synthetic activity. Some works demonstrated an important role of cilia in the mechano-transduction of chondrocytes. Chondrocyte cilia are oriented either toward the articular surface or toward the subchondral bone: the orientation toward the articular surface is more pronounced in chondrocytes of load-bearing cartilage than in those of non load-bearing cartilage, suggesting the involvement of cilia in mechano-transduction. Moreover, cilia are the compartment where integrins, Ca2+ and other molecules known to be mechano-transducers are located (16-17).

Thanks to this mechano-sensitivity, chondrocytes are able to activate anabolic or catabolic pathways, depending on the surrounding mechanical environment, and modulate the composition of the cartilage matrix.

When the load is drastically reduced (i.e. as a consequence of the rigid immobilization of a limb), the matrix composition is depleted, in particular in regards to the proteoglycan compartment, presenting a reduced resistance to compression but a constant resistance to tension. This cartilage response is reversible, so when normal load is restored, the matrix is once more enriched of proteoglycans and the biochemical and mechanical properties are restored. However, when the load is significantly increased (i.e. as a consequence of trauma or aging), chondrocytes activate catabolic pathways leading to the release of proteolytic enzymes that degrade the cartilage matrix which in turn leads to degeneration of the tissue (18-19). Some studies demonstrated that extreme physical training, such as marathon, may induce increased joint matrix turnover, characterized by collagen and proteoglycan breakdown, as observed in runners after a long distance run. In particular, the patellofemoral joint and the medial compartment are the most involved areas of such degeneration (20-22). So, chondrocytes are able to feel the fine balance of the mechanical stresses in the knee joint, thus promoting the renewal of the cartilage matrix when the load is within the physiological range or activating matrix degradation when the load is outside the range.

REGENERATIVE LIMITATIONS OF ARTICULAR CARTILAGE

Although articular cartilage is a metabolically active tissue, it has a poor intrinsic healing potential when damaged. There are two main reasons for the limited cartilage response to traumas: firstly, the cartilage is an avascularized tissue, therefore when a cartilaginous lesion occurs, neither blood clot formation nor an inflammatory response can take place. Secondly, it lacks undifferentiated cells. In fact, the highly differentiated chondrocyte is the only cell type present in cartilage, characterized by a limited synthetic and mitotic potential (23). However, it is important to remember that, despite the limited regenerating potential of this tissue, chondrocytes are isolated from the attack of the immune system as no immune cells or immunoglobulins are present in the surrounding matrix, as mentioned before: this is a kind of privilege with respect to other tissues as it allows the use of allogenic transplantation for the repair of a lesion, such as the use of osteochondral allograft, cartilage fragments and allogeneic chondrocytes combined with biomaterials (24-26).

Different types of lesions can affect the hyaline cartilage, leading to different repair responses. Generally, cartilage lesions can be divided into superficial lesions, blunt traumas and subchondral bone injuries.

Superficial lesions (partial thickness defects)

The damage starts with collagen fibrillation at the top of the articular surface. In this stage, the histological proteoglycan specific stain (safranin-o) diminishes as a result of the lack of proteoglycans. Chondrocytes proliferate in clusters and start producing a large amount of proteoglycans, but they do not migrate nor fill the defect; the newly synthesized proteoglycans remain close to the chondrocyte clusters. Moreover, superficial lesions increase both the permeability of the tissue and the direct biomechanical response of the macromolecular framework during compression. If the damage progresses, fragments of articular cartilage may be released into the joint thus exposing the subchondral bone. As a result, the load is directly transmitted to the underlying subchondral bone, producing an increase in its density and thickness.

Blunt trauma

High load shocks and single, multiple, or repetitive lower load traumas may generate a chondral lesion without any visible alteration of the superficial area. In particular, in a blunt trauma, the load is transmitted throughout the whole thickness of the tissue to the deepest layers; the osteochondral bone reacts and becomes progressively thicker. This could cause a reduction in the capacity to absorb shocks at this level, eventually leading to the deterioration of the cartilage layers above (27).

Osteochondral lesions

This type of damage consists of a full thickness cartilage defect extending into the underlying subchondral bone. These lesions therefore have access to bone marrow cells like blood cells, macrophages and mesenchymal stem cells, hence enhancing the rapid development of a fibrin clot in the defect and bony portion of the lesion. After a few days, mesenchymal stem cells then migrate from the bone marrow to the periphery of the blood clot and start differentiating into chondrocytes and osteoblasts in the bony part and, within a few weeks, they fill the defect. Due to the stimulation of local growth factors, these cells start producing collagen type II, collagen type I and the macromolecules of the native articular cartilage. However, since these components are less than those of the normal cartilage, the reparative cells cannot arrange the molecules into a normally organized layered structure. Furthermore, this reparative process is often incapable of restoring the superficial zone completely. The reparative tissue, having properties that are intermediate between cartilaginous and fibrous tissue, is therefore unable to restore the normal structure, composition and mechanical properties of the hyaline cartilage (28).

CONCLUSIONS

The biochemical composition and the morphological organization of articular cartilage are fundamental for the correct biomechanical function of this tissue. In physiological conditions, the extracellular matrix and the joint environment allow the cartilage tissue to give a biomechanical response with minimal or absent tissue consumption and degradation. However, when a lesion occurs, the remaining cells are not able to organize an adequate regenerative response or, in case of an osteochondral lesion, the infiltrating cells fail in the attempt to organizing the newly formed tissue into a biomechanically functional matrix.

Therefore, especially in large lesions involving weight-bearing areas in adult patients, this leads to a long-term failure of the reparative tissue, making the defect of the articular cartilage one of the most problematic and challenging issue for the orthopedic surgeon.

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NARRATIVE REVIEW

OBJECTIVE FUNCTIONAL ASSESSMENT IN THE DEFICIENT AND RECONSTRUCTED ACL - A SHORT REVIEW

A. CACCHIO[1], F. BORRA[2] and G. SEVERINI[3]

[1] Dipartimento di Medicina Clinica, Sanità Pubblica, Scienze della Vita e dell'Ambiente, Facoltà di Medicina, University of L'Aquila, L'Aquila; [2]Fisiology Center, Forlì; [3]Catholic University of the Sacred Heart, Rome, Italy

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Arthroscopic reconstruction of anterior cruciate ligament (ACL) has evolved to less invasive, more anatomical approaches. Consequently, post-operative rehabilitation has likewise become more progressive and innovative. On the other hand, few objective, functional criteria are used to determine when patients with ACL reconstruction can return to sports activities. In recent years technologies in the field of functional evaluation have been enormously developed, allowing an easier and more accurate assessment of knee motion during athletic activities. Thus, the purpose of this paper is to summarize the evidence from biomechanical studies on ACL-related research, encouraging orthopedic surgeons, physiatrists, physiotherapists and athletic trainers with related background to better understand biomechanics, injury aetiology, prevention, rehabilitation, stability assessment, and adaptations after reconstruction for patients with ACL injury. Level of Evidence: 5 - Narrative Review

Anterior cruciate ligament (ACL) is the most commonly injured ligament in the knee leading to instability, difficulty in returning to pre-injury sport levels and early interruption of a sporting career (1). Therefore, the ultimate goal of ACL arthroscopic reconstruction, followed by rehabilitation treatment, is the restoring of the patient's functional knee stability to prevent re-injury and allow a safe return to previous activity levels (2). However, in spite of the high incidence of ACL injuries, especially in soccer players (3), and abundant related literature, there is still no consensus about the optimal surgical technique for its reconstruction (4) and even less agreement on the ideal rehabilitation strategy following surgery (5).

Moreover, standardized and objective criteria to assess athletes' safe return-to-sports are poor and, despite the progress in ACL reconstruction techniques and rehabilitation procedures, two-thirds of athletes who underwent ACL reconstruction do not return to pre-injury sports levels (6). Among the athletes who return to their pre-injury sports levels, ACL re-injury occurs in 3% to 19% of ACL-reconstructed knees, and 5% to 24% of athletes sustain a contralateral ACL injury (7).

In absence of standardized methods of assessing knee function and stability after ACL reconstruction, especially for return to sports activities, most clinicians use a combination of criteria: namely, functional, clinical, and subjective testing. Usually, this includes achievement of full range of motion, negative pivot-shift test, quadriceps and hamstring

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Mailing address: Prof. Angelo Cacchio,
Dipartimento di Medicina Clinica, Sanità Pubblica,
Scienze della Vita e dell'Ambiente,
Facoltà di Medicina, Università degli Studi dell'Aquila,
P.le Salvatore Tommasi 1,
67100 L'Aquila, Italy
e-mail: angelo.cacchio@univaq.it

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strength which approximates that of the uninvolved side, and functional testing scores that approximate the contralateral side (8). Lachman test, pivot shift test, KT-1000 or -2000 (MEDmetric, San Diego, California) arthrometer test, and isokinetics tests have been normally used to determine when to resume sports activities. Among these, even today, one of the most commonly used parameter to determine recovery and readiness to return to sports following an ACL reconstruction is achieving 85% of the maximal quadriceps strength of the contralateral limb, assessed by an isokinetic dynamometer. Recently, Yabroudi and Irrgang reported that a minimum quadriceps strength index value of 70% to 75% for running, 80% for submaximal agility training, and 85% for sport-specific skill training are recommended after an anatomical ACL reconstruction (9-10). However, some studies have shown that these tests are not reliable predictors of the functional stability of the knee in sports activities (11-12).

In a recent review, although the great majority (nearly 90%) of athletes reached what is considered normal or near-normal isokinetic strength values (greater than or equal to 85% to 90% of muscle strength capacity in their injured leg compared to their non-injured leg) for a safe return to sport, the rate of return to sports was low (13). This suggests that commonly used muscle strength tests as criteria to return athletes to unrestricted sports activities after ACL reconstruction are not exhaustive enough, or that variables more important for safe return to unrestricted sports activities are not being evaluated after ACL reconstruction.

Some authors suggest to use functional tests as the one-leg single hop for distance, the one-leg triple hop for distance, the one-leg timed hop, and the one leg cross-over hop for distance, and vertical jump, comparing the results of the injured limb with the uninjured one (9). Also in this case, literature suggests to achieve a measurement of 80% to 85% in the injured leg compared with the uninjured leg before returning to the sport (9). The limb symmetry index (LSI) is commonly used as an outcome measure when the one-leg hop for distance test is used as test. LSI (%) is calculated as injured leg/uninjured leg x 100 (14).

However, as suggested by Clark (14), it should be acknowledged that functional tests may not be truly sport-specific as many clinicians state.

Recently, a functional test as the drop jump was questioned with respect to its ability to predict non-contact ACL injury. As suggested by Kristianslund and Krosshaug (15), there was a substantial difference in kinematics and kinetics between drop jumps and sport-specific sidestep cutting, a movement much more related to the on-field performed movements.

This shows that there is a continuous need to develop better criteria for a safe return to sports, and recently there have been many efforts toward that goal.

A strength test battery, which includes knee extension, knee flexion, and leg press muscle power tests, can significantly reveal deficits in leg muscle power in patients with ACL deficiency or ACL reconstruction (16).

Moreover, a recent study (17) highlighted that, despite the near recovery of MVIC strength to pre-injury levels, there were still significant deficits in rate force development at 6 months post–ACL reconstruction. An RFD similar to the pre-injury RFD was achieved at 12 months post–ACL reconstruction, following a rehabilitation program focusing on muscle power. These results suggest that, following an ACL reconstruction, RFD criteria may be a useful adjunct outcome measure.

Currently, based on objective criteria, there is no consensus as to when athletes should safely return to their pre-injury sport level after ACL reconstruction and post-surgical rehabilitation, especially in sports activities requiring high dynamic neuromuscular control with power generation and absorption (2).

In general, it could be recommended that return to play should occur when there is no pain, no instability, near symmetrical performance compared with the contralateral limb, and normal kinematics (18).

Therefore, before recommending "ACL-reconstructed patients" to return to activity at pre-injury level, we need to have a more detailed functional assessment of the injured knee/limb. This particular assessment would measure knee stability when performing similar on-field movements in the laboratory of movement analysis setting. Functional knee stability, evaluated by 3-D movement analysis, could provide valuable information on standardization for safe return-to-sports.

This paper aims to describe the basic biomechanics of the knee, and the importance of movement analysis assessment in the evaluation of the stability of the knee for injury diagnosis, evaluation of treatment, and the safe return to sports in ACL deficiency and ACL reconstructed knee.

Basic Knee Biomechanics

The knee joint has three main axes of movement: longitudinal (tibial shaft axis), transversal (epicondylar axis), and sagittal (anteroposterior axis), six degrees of freedom with three translations: proximal-distal, medial/lateral, and anterior/posterior and three rotations: flexion/extension, internal/external, and abduction/adduction (19).

Due to the low anatomical congruity between femur and tibia, the knee joint obtains just modest stability from the bones. The menisci enhance this stability through improved joint congruity, but functional stability is ensured by ligaments, capsule, and the musculo-tendinous soft tissues that surround the knee joint (20).

The primary role of the ligaments of the knee is to provide stability to the joint throughout its range of motion. Each ligament plays a role in providing stability in more than one degree of freedom as well as restraining knee motion in response to externally applied loads. Overall, dynamic stability depends on integration of articular geometry, soft tissue restraints, and the loads applied to the joint through weight bearing and muscle activation.

Generally, several ligaments work synergistically to provide joint stability. In addition, joint compressive forces, during weight bearing activity, provide additional stability and the neuromuscular system regulates joint motion, particularly through a co-contraction mechanism. Co-contraction regulates joint motion, but also increases joint stiffness by increasing joint compression. When performing an unpractised exercise, increased co-contraction is present. However, as a skill is acquired by practice, the activation of the antagonist muscle is reduced, and the efficiency of the movement is increased (21). After an ACL injury, some patients can maintain knee stability in dynamic situations despite a mechanically unstable knee. It has been described that patients with ACL deficiency who do not function well after injury (non-copers) use a joint stiffening strategy with increased co-contraction. On the other hand, patients who are able to compensate ACL deficiency (copers) use a movement pattern that is closer to normal (22).

The ACL is a band of dense connective tissue which runs from the femur to the tibia. Most anatomical studies (23-25) suggested that ACL have two different bundles: the antero-medial (AM) bundle and postero-lateral (PL) bundle.

Biomechanical studies showed that AM bundle, due to its more vertical position, contributes mainly to antero-posterior stability (anterior tibial shear), while the PL bundle, due to its more oblique position, mainly contributes to rotational stability of the knee joint (26-28). Despite the complex role of the ACL in the stabilization of the knee joint, initial biomechanical studies of the ACL focused mainly on its function of resisting anterior shear of the tibia on the femur. This influenced the surgical procedures for ACL reconstruction, so that the traditional methods of arthroscopic of ACL reconstruction that used a single bundle bone-patellar-tendon-bone or hamstrings autograph restored the anterior tibial shear, but not the tibial rotational stability (29). Moreover, some clinical studies suggested that biomechanical considerations of anterior tibial shear alone do not correlate with subjective evaluations of knee stability (30). Therefore, in recent years some basic and clinical studies have focused closer attention on the rotational stabilizing function of the ACL (26, 31-32), providing the biomechanical rationale to the recent emergence of an anatomical double-bundle ACL reconstruction approach (33-34) to better restore the biomechanics in the ACL reconstructed knee.

ACL reconstruction

The aim of an ACL reconstruction is to regain knee stability. However, several studies have shown that an ACL reconstruction can reduce the static knee laxity, but all techniques do not seem to restore normal tibio-femoral kinematics (4, 32, 35-37). Currently, there is no consensus regarding the optimal surgical technique and the graft choice for ACL reconstruction. Single bundle with bone-patellar tendon-bone graft or hamstring graft are the most frequently used procedures. However, using this traditional procedure, only 61% to 67% of patients achieved normal IKDC score (38), and 40% to 90% of patients have radiographic knee osteoarthritis 7 to 10 years after reconstruction (39-40).

In the last decade, improvements in the understanding of the anatomy and function of the native ACL have lead to increasing interest in reconstructing both bundles of the ACL (41-42).

Generally, traditional single-bundle ACL reconstruction successfully restores normal anterior/posterior translation but fails to restore normal rotational stability (29, 43). These observations have been confirmed in an *in vivo* study that used dynamic dual-video fluoroscopy to evaluate the kinematics of the knee during walking and running on a treadmill in patients who underwent traditional, non-anatomic, single-bundle reconstruction (32). Since conventional single-bundle ACL reconstruction appears not to restore the normal kinematics of the knee, it is hypothesized that this inability is one of the factors that may contribute to the development of knee osteoarthritis after ACL injury and reconstruction. In contrast, it appears that ACL reconstruction using double-bundle techniques better restores rotational stability compared to single-bundle reconstruction (43).

However, these better results may be due to the anatomic placement of the ACL and not necessarily to the double-bundle technique. Yamamoto et al (44) showed that single-bundle ACL reconstruction performed in an anatomic fashion can restore knee kinematics to a level similar to that achieved by anatomic double-bundle reconstruction when the knee is near full extension; however, double-bundle reconstruction resulted in more normal kinematics when the knee was at higher angles of flexion.

The clinical evidence for double-bundle ACL reconstruction is mounting but is still inconclusive. Some biomechanical studies have demonstrated increased overall stability following double-bundle reconstruction relative to a single-bundle technique, while others have not (34, 45-47). Furthermore, while some clinical studies have demonstrated improved stability measurements with double-bundle techniques, improved clinical outcomes have not been consistently demonstrated (47-50).

In a meta-analysis by Meredick et al. (50) it was demonstrated that double-bundle ACL reconstruction resulted in significantly better side-to-side differences in anterior tibial translation as measured with the KT1000 arthrometer, and a significantly higher proportion (88% of patients who underwent double-bundle vs. 62% of 62% of those who underwent single-bundle) normal pivot shift tests.

Clinical and Biomechanical Evaluation

To better understand the differences in outcome of ACL reconstruction, the use of in vivo motion analysis systems can be a valuable tool for orthopaedic surgeons, physiatrists, physical therapists, team physicians, athletic trainers and other members of teams involved in the treatment of ACL deficiency and reconstruction.

In recent years, a number of in vivo studies have examined the biomechanics of ACL-deficient and ACL-reconstructed knee motion during various physical activities, influencing surgical and rehabilitation protocols.

These studies are based on the concept of "motion capture" that Alberto Menache (51) defined, in the first chapter of his book, as: "the process of recording a live motion event and translating it into usable mathematical terms by tracking a number of key points in space over time and combining them to obtain a single 3D representation of the performance.". Motion capture allows to quantify and to measure the movements of a human body during the execution of a defined motor task, and its use is now extended to different fields of human movement, both healthy and pathological: biomechanics, rehabilitation, orthopaedics, sports science, and other related fields (52).

In some of these fields the goal has been to develop models of the human body that explain how it functions mechanically and how one might increase its movement efficiency (52).

Over the years many systems have been developed to perform the motion capture of the human body. The two main branches of the motion capture systems are represented by optical and non-optical systems. The non-optical systems, include accelerometers, electrogoniometers, and electromagnetic devices.

Electrogoniometers are devices used to measure joint angles. However, since these tools are not attached to an external body landmark (e.g. in proximity to the joint centre), but instead are positioned above the two body segments spanning the joint, they measure the angle between the two sensors attached to the body segments. Their measures are based on the assumption that they move consensually with the midline of the limb segment onto which they are attached, and therefore they measure the actual angle of the joint (53). Advantages of electrogoniometers include relatively low cost, ease of set up and processing, portability for data collection out of the workplace. Disadvantages include the lack of data with respect to the global reference system and 6-DOF, errors due to alignment of the axes of rotation, difficulty in monitoring joints surrounded by large amounts of soft tissue (such as the hip).

Accelerometers work on the principle of inertia. Currently, in clinical practice, triaxial accelerometers are used, which are piezoresistive devices, that can be attached to various parts of the human body to measure 3-D accelerations (54). Disadvantages include signal "drift" which creates increasing artifact over time, and the need to determine the following to accurately calculate a segment's acceleration and velocity: the segment's initial position and velocity values, the effects of gravity, and identification of the segment's rotational DOF. Nonetheless, the acceleration output from accelerometers is instantaneous, and they are useful when basic acceleration information of body segments is of primary interest in an investigation, for real-time biofeedback, and for data collection in the field (55). Advantages of accelerometers include relatively low cost, small size, and measurement of rotational segmental motion.

Gyroscopes are angular velocity sensors that can be easily attached over several segments of the human body to record angular velocity-time plots. Since lower limbs exhibit a specific pattern derived by angular-velocity-time plots, these data can be processed to derive various spatial-temporal events and parameters of gait such as step/stride lengths, velocity, stance/swing times. The advantages of gyroscopes are their possible use in outdoor environments, the direct measurement of rotational motion that is not influenced by gravity, and small size. Disadvantages include increasing error of several degrees per second caused by gyroscope offset and noise.

Electromagnetic systems are based on low-frequency magnetic coils that permit real time 6-DOF tracking of segments by sensors placed on the segments (56). Limitations include interference from metallic objects or other magnetic fields which will degrade performance, cabling to connect sensors which can inhibit movement, slippage of the sensors, number of sensors (usually up to four) that can be tracked at one time, and cost. Advantages include the elimination of marker dropout from the camera field of view, real time 6-DOF data, and accuracy.

The optical systems generally capture 3D motion data in an automated and synchronized fashion and employ: *a)* opto-electronic digitizers in which high-speed cameras capture passive (reflecting light) or active (generating light) markers placed on specific anatomical bony landmarks of the subject, to track the changing positions and orientation of body segments during a given movement (kinematic); *b)* floor mounted force plates to measure the magnitudes and directions of the resulting forces exerted on the ground (kinetic); *c)* surface electromyography (sEMG) electrodes to record the sequence and timing of muscle activity (neuromuscular activations) (57).

The main disadvantages are cost, complexity of setup and calibration with a relative long learning curve, the relative motion between the markers and the skin. Moreover, if the number of high-speed cameras is low, the reconstruction of the movement during the execution of complex motor tasks may be difficult due to the "masking effect" of some markers. However, reliability and validity studies of these systems have shown that errors are usually small enough to allow for accurate data acquisition, elaboration and interpretation. (58).

Three-dimensional biomechanics analysis of the tibio-femoral joint can be evaluated using roentgen stereophotogrammetric analysis (RSA) (59). However, although RSA provides a direct measurement of in vivo bony motion, its clinical use is limited by the exposure to radiation required by the procedure.

Over the last decade, the use of 3-D opto-electronic systems has allowed the publication of several biomechanical studies about the effect of ACL deficiency and reconstruction on different motor tasks such as walking, running, pivoting, cutting, ascending and descending stairs, etc. (37, 60-62).

These studies have demonstrated that, firstly, ACL deficient knees result in an increased anterior tibial shear and in an increased internal tibial rotation in relation to femur in comparison to the uninjured knees, and, secondly, conventional single-bundle ACL reconstruction does not completely restore the normal biomechanics of an ACL-intact knee both during low-stress (i.e., walking) and high-stress (i.e. pivoting, cutting, etc.) motor tasks. In fact, although anterior tibial shear seems to be reasonably reconstituted, some studies analyzing the biomechanics of the knee during motor tasks with different level of ACL-stress after ACL reconstruction with a variety of grafts (e.g., BPTB vs. hamstring), and positions of fixation (e.g., ten vs. eleven o'clock position), reported the persistence of an increased tibial internal rotation, compared to ACL-intact knee (37, 60-64).

It has been shown that the knee rotatory instability persists even after 2 years from the ACL reconstruction (65).

Another interesting aspect that has been shown is that most on-field ACL injuries occur in cutting, jumping and single-leg landing maneuvers (66-68).

In a recent three-dimensional kinematical analysis of injury situations in handball and basketball female teams, knee valgus motion has been identified as an important component of the ACL injury mechanism (69).

Since the initiation and progression of knee joint OA in patients with ACL injury has been linked to abnormal knee joint biomechanics during dynamic in vivo activities (70-71), many efforts are being made in an attempt to provide patients with an ACL reconstruction technique that better reproduces the biomechanics of the ACL intact knee.

Recently, in vitro cadaveric studies have documented that we could have better biomechanical results with an anatomic reconstruction procedure with double-bundle than with the single-bundle reconstruction (29, 34, 43). Steckel and colleagues using a computer tracking technique to model the motion of the femur on the tibia during flexion have also demonstrated in five cadaveric knees that both single- and double-bundle procedures restored an anterior translation comparable to the intact knees at 0° flexion, but the double-bundle group was significantly more stable at 15° and 75° of flexion. At Lachman and anterior drawer tests the double-bundle knees also were significantly more stable compared to the single-bundle knees. Moreover, when rotatory stability was assessed, the single bundle showed significantly less stability than the intact or double-bundle knees.

However, although the restoration of knee rotational stability after double-bundle ACL reconstruction has been made in the cadaveric studies, limited data exist on biomechanical studies carried out with motion analysis. Currently, only two studies have analyzed knee biomechanics using motion analysis after ACL reconstruction with double-bundle technique, and their results are inconclusive. In one of these studies, Lam and colleagues showed that anatomic double-bundle ACL reconstruction restores knee rotational stability within normative levels during a pivot task (72). On the other hand, the study by Misonoo and colleagues (73) that evaluated tibial rotation during a cutting task found that both single- and double-bundle ACL reconstruction equally limit tibial rotation. Therefore, since both single- and double-bundle ACL reconstruction equally restored the knee sagittal plane biomechanics, further biomechanical and clinical studies will be required to provide insight on whether the high cost, increased technical complexity and possibly increased complication rate of the double-bundle ACL reconstruction is justified by better restoration of knee transverse plane biomechanics.

The meta-analysis by Meredick and colleagues (50) and three out of six successive randomized clinical trials comparing double-bundle ACL reconstruction to single-bundle ACL reconstruction (49, 74-75) demonstrated that double-bundle ACL reconstruction resulted in significantly better side-to-side differences in anterior translation and a significantly higher proportion of normal pivot shift tests. However, none of these studies have demonstrated that double-bundle ACL reconstruction results in better patient-reported outcome. The limitations of currently available clinical outcome measures must be considered when comparing single-bundle to double-bundle ACL reconstruction.

CONCLUSIONS

In the future, long-term follow-up studies are needed to determine the effects of anatomic double-bundle compared to single-bundle ACL reconstruction on: *a)* the sense of instability and the ability to participate in strenuous sports, and *b)* preventing or reducing the risk of knee osteoarthritis and its associated pain and disability.

In this direction, we think that traditional assessments of ACL deficiency and reconstruction should be complemented by objective functional assessments performed with movement analysis systems. From a clinical perspective this short review overall suggests that: (*a*) surgeons should endeavour when possible to placing the graft in a position that better controls tibial internal rotation, and (*b*) physicians, physical therapists, trainers, etc., should take extra care to excessive tibial internal rotation showed by patients with ACL deficiency and reconstruction, introducing suggested objective assessments, as well as specific functional exercises in their rehabilitation and return to sports protocols.

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