Autologous Chondrocyte Implantation Postoperative Care and Rehabilitation

Science and Practice

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Autologous chondrocyte implantation is an advanced, cell-based orthobiological technology used for the treatment of chondral defects of the knee. It has been in clinical use since 1987 and has been performed on 12 000 patients internationally; but despite having been in clinical use for more than 15 years, the evidence base for rehabilitation after autologous chondrocyte implantation is notably deficient. The authors review current clinical practice and present an overview of the principles behind autologous chondrocyte implantation rehabilitation practices. They examine the main rehabilitation components and discuss their practical applications within the overall treatment program, with the aim of facilitating the formulation of appropriate, individualized patient rehabilitation protocols for autologous chondrocyte implantation.

Keywords: rehabilitation; cartilage repair; autologous chondrocyte implantation (ACI); knee; patellofemoral; tibiofemoral

Intact articular surfaces are necessary for adequate joint function, as they enable smooth movement and protect the joint against wear by reducing the coefficient of friction and by attenuating peaks of stress. However, damaged articular cartilage has a limited potential for self-repair, and restoration of an adequate articulating surface remains a formidable challenge. Controversy still exists as to whether microfracture, autologous osteochondral grafting, or cultured autologous chondrocyte implantation (ACI) is the best repair technique and to which lesion each should be applied. Numerous attempts to repair damaged articular cartilage have been met with similar problems: inability to produce hyaline cartilage, poor integration with the surrounding cartilage, and gradual deterioration of the repair tissue.[2,24,137]

Autologous chondrocyte implantation is an advanced, cell-based orthobiological technology used for the treatment of chondral defects of the knee. This first orthopaedic tissue-engineered procedure has been in clinical use since 1987 and has been performed on more than 12 000 patients internationally. It has demonstrated significant and durable benefits for patients in terms of diminished pain and improved function.[1,23,113,114] Autologous chondrocyte implantation has always been, and continues to be, very strictly regulated; today it is the most widely researched clinical cartilage repair technique. Despite the fact that ACI has been in clinical use for more than 15 years, the evidence base for ACI rehabilitation is notably deficient. Consequently, to date, guidance for ACI rehabilitation has been predominantly based on a combination of expert opinion, animal studies, basic science, and clinical biomechanics. The objective of this article is to provide an overview of the current understanding, issues, and areas of debate with regard to ACI rehabilitation.

PROCEDURE AND VARIATIONS OF ACI

The classic autologous chondrocyte transplantation (ACT) was described by Brittberg et al[23] as the first generation of a cell transplantation technique for cartilage repair, based on the implantation of a suspension of cultured autologous chondrocytes beneath a sealed periosteal cover. The technique is characterized by the combination of 2 chondrogenic factors: the implanted suspension of chondrocytes and the cambium cells of the periosteum.[24] The surgical steps include arthrotomy, preparing the defect, periosteal harvest, suturing

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No potential conflict of interest declared.

The American Journal of Sports Medicine, Vol. 34, No. 6
DOI: 10.1177/0363546505281918

the periosteum over the defect, testing for water-tightness, application of fibrin glue sealant, chondrocyte implantation, wound closure, and rehabilitation.[100] This procedure has certain disadvantages, including the potential leakage of chondrocytes from defects, the dedifferentiation of a cellular phenotype (because the cells are grown in monolayer before implantation), the uneven distribution of cells, and the risk of periosteal complications.[24,87,88] Early problems include periosteal graft detachment and delamination as well as late periosteal hypertrophy.[114]

The second generation of ACI includes the use of a bilayer collagen membrane instead of the periosteal flap. These purpose-designed biomaterials are sutured over the prepared cartilage defect, and the cell suspension is injected underneath. The use of a collagen membrane simplifies the surgical procedure and reduces the number of the incisions to 1, thus reducing the overall surgical morbidity. Furthermore, the complication rates of periosteal hypertrophy may be reduced.[54]

Further technological advances have led to the third generation of ACI, which uses biomaterials seeded with chondrocytes as carriers and scaffolds for cell growth. This composite "all-in-one" tissue-engineered approach combines cultured chondrocytes with 3-dimensional biocompatible scaffolds for the purpose of generating new functional articular tissue. The 3-dimensional scaffolds have been shown to contain the chondrocytes in the defect area and to support the maintenance of a chondrocyte-differentiated phenotype.[52,53,128] After debridement of the defect, the biomaterials with seeded cells are trimmed to exactly match the defect size and are implanted without the use of a periosteal cover or fixing stitches. In most techniques, only fibrin glue is used for the fixation of the graft. Because there is no requirement for periosteal harvest or stitching the cover over the recipient site, a mini-arthrotomy technique can be used. Although the lack of firm fixation is a concern, Marlovits and collaborators[89] reported that the implantation and fixation of a cell-scaffold construct (matrix-induced ACI [MACI]) in a deep cartilage defect of the femoral condyle with fibrin glue and with no further surgical fixation lead to a high attachment rate 34.7 days after the implantation, as determined with high-resolution MRI.[89]

When planning to restore the articular defect, the surgeon must diagnose and correct any significant comorbidity: a meniscal deficiency, ligament laxity, or mechanical malalignment of the tibiofemoral or patellofemoral joint. Uncorrected meniscal deficiency and ligament laxity are a contraindication to cartilage restoration procedures. Most lateral patella and trochlear cartilage restoration procedures should be combined with arthroscopic lateral release, preferably at the time of chondral biopsy. The patellar realignment procedure, principally aimed at medialization of the patella to unload the newly restored articular surface, should be performed at the time of open chondrocyte implantation. Medial patellofemoral chondral lesions may be an exception to this principle and may require patellar anteriorization. The role of the hinged patellar brace and incremental increase of knee flexion remains unclear. A high tibial osteotomy is required to correct the varus angulation of the lower limb mechanical axis to just beyond neutral when performing a cartilage restoration procedure in the medial compartment of a varus knee. The use of an unloading brace should be considered for postoperative rehabilitation. For valgus angulation of a knee joint, a distal femoral osteotomy is required to restore the mechanical axis to neutral. It is important to carefully plan a sequence of surgical and rehabilitation options and to consider staging procedures if needed.[2]

This article deals with the rehabilitation of cartilage repair with cultured autologous chondrocytes, and from this point onward, we will refer to all the different open chondrocyte implantation techniques (ACI, ACT, MACI, MACT) as ACI.

PRINCIPLES OF ACI REHABILITATION

Despite the fact that ACI is the most widely researched cartilage repair technique, there are currently only 2 articles that specifically address rehabilitation protocols.[8,14] Rehabilitation after ACI is a long and demanding process that presents challenges to clinicians and patients alike. Autologous chondrocyte implantation rehabilitation differs from other articular cartilage reparative or restorative procedures in 4 pertinent ways: indication, surgical procedure, graft maturation, and evidence base.

Indication

The ACI procedure is predominantly for larger lesions (>2 cm^2),[2] and this indication presents implications for rehabilitative joint loading and the potential for graft disruption, especially when lesions are poorly "shouldered."[85] Autologous chondrocyte implantation is also indicated as a secondary treatment after 1 or more failed alternative cartilage repair procedures, which has rehabilitative implications associated with symptom duration and surgical morbidity.

Surgical Procedure

In contrast to other cartilage repair procedures, ACI is currently a 2-stage procedure that is often undertaken with concomitant procedures, as previously highlighted. The staging of procedures therefore needs to be considered and planned to avoid competition between postoperative rehabilitation protocols. After the arthroscopic biopsy, sufficient time should be allowed before the cell implantation for the restoration of joint homeostasis. Initial autologous chondrocyte culture time was 6 to 8 weeks, but this has already been halved to 3 to 4 weeks and has potential for further reduction with emerging tissue engineering technologies. However, even without any concomitant procedures, a minimum of 3 weeks is needed after arthroscopy[148] to replace lost synovial fluid, to allow portal wound healing, to allow recovery from analgesia/anesthetic, and to advance into the remodeling/maturation phase of healing. The implantation stage is routinely performed via either open arthrotomy or mini-arthrotomy, resulting in greater surgical trauma and mechanoreceptor disruption, all of which are likely to entail a longer rehabilitation process for return to function compared with alternative arthroscopic cartilage repair procedures.

Graft Maturation

For optimal results, ACI rehabilitation needs to not only follow but also to facilitate the process of graft maturation. Excessive or inappropriate loading of immature neocartilage is therefore not advisable. However, the difficulty arises in the longitudinal assessment of the maturation status of the graft. Graft remodeling and maturation can continue for up to 3 years after ACI implantation,[69] and the length of this process consequently has significant implications for the timing and specifics of the rehabilitation protocol.

A broad timeline for maturation of the ACI graft has been proposed, based on studies in a dog model as well as clinical observations such as second-look arthroscopy, MRI, and patient symptoms.[18,123] However, at this point, there is no established and verified ACI graft maturation timeline.

Canine studies have demonstrated that there are several stages to the healing process.[19] The *proliferative* stage, which seems to last up to 6 weeks, is characterized by a primitive cell response, with tissue fill of the defect. During the *transition* stage, the tissue is not firm or well integrated, and it feels very soft, almost liquid, when probed with an arthroscopic probe. At this stage, a type II collagen framework is produced along with the proteoglycans that form the cartilage matrix. By 3 to 6 months, the tissue has usually firmed up, it has a gelatin-like consistency, and it is well integrated to underlying bone and adjacent cartilage. Patients will start to experience good symptom relief during this period. At 6 to 9 months, the neocartilage is putty-like. A *remodeling and maturation* phase occurs over time, lasting as long as 2 years as matrix proteins crosslink and stabilize in large aggregates and the collagen framework reorganizes to integrate into the subchondral bone and to form arcades of Benninghoff. However, the process of tissue maturation that begins during the remodeling stage continues long after this point. Excessive activity during this remodeling stage may cause repair tissue degeneration. Hence, the concept of a timeline of graft healing and remodeling is critically important during ACI rehabilitation.[98]

An increasingly effective, noninvasive method of assessing articular cartilage repair[6,10,22,27] and, more specifically, ACI graft maturation[15] is advanced MRI. In particular, MRI can evaluate the degree of defect fill-in, the integration of the neocartilage to the subchondral bone plate, and the status of the subchondral bone plate and bone marrow. The signal intensity of ACI repair tissue is variable and may be heterogeneous. To our knowledge, no longitudinal studies showing the progression of the signal intensities in maturing ACI grafts have been performed. The clinical experience of Alparslan and coauthors[4] has shown that ACI grafts may have a relatively bright signal on fat-suppressed fast spin-echo images during the initial weeks after surgery (proliferative phase), and some areas of bright signal may persist for several months after the surgery (transitional phase).[4] The mature, intact ACI repair tissue may appear similar in signal intensity to normal cartilage, mildly brighter or darker than normal articular cartilage, or heterogeneous, with a layered or speckled pattern. However, Alparslan and coauthors[4] found that a linear, fluid-like signal, either within the ACI or at its junction with the subchondral bone, usually indicates tear of the periosteal cover or poor integration of the graft, with in situ delamination. A small, cross-sectional qualitative study of the appearance of ACI on MRI found heterogeneous signal intensity to be common within the graft site during the first 3 months, whereas at 1 year the repair cartilage appeared more uniform. After contrast enhancement, grafts during the first 3 months showed heterogeneous uptake of gadolinium–diethylenetriamine pentaacetic acid (Gd-DTPA), whereas grafts between 3 months and 1 year showed very little enhancement. On MRI, the repair tissue within the ACI site should ideally appear as thick as the adjacent native articular cartilage and should have a smooth articular surface that reproduces the original articular contour. When an osteochondral defect is present preoperatively, however, the subsequent thickness of the repair cartilage is usually thicker than that of native cartilage, but the original articular contour is restored. The margins of the graft should be continuous with the adjacent native articular cartilage, with an indiscernible or linear interface. The signal intensity of the junction between the ACI and native cartilage may appear dark, indistinguishable from cartilage, or as bright as fluid. Interestingly, fluid-like signal at these margins may be present with an intact surface and does not necessarily imply that a fissure is present, as long as the fluid-like signal does not extend beneath the remainder of the graft. The clinical significance, if any, of the different signal intensities at the ACI margin is presently unknown.

The subchondral bone plate beneath the ACI may appear either smooth or slightly irregular. If the ACI was performed to repair an osteochondral defect, the level of the subchondral bone plate will be below that of adjacent areas, but the ACI repair tissue should still reproduce the articular contour. Edema-like signal within the bone marrow subjacent to the ACI site is an expected finding in the early postoperative period. In mature grafts, however, the marrow signal intensity is usually normal or may demonstrate only minimal, linear bright signal on fat-suppressed images. It is still unclear when the subjacent bone marrow signal should return to normal. Subchondral changes and edema of the underlying bone marrow are being reported increasingly frequently,[5] and it is suggested that these are normal responses to ACI and reflect graft remodeling and attachment to the subchondral bone.[55] If that is the case, then from a rehabilitation perspective, it would be beneficial to know when persistent changes are indicators of abnormal responses to ACI, but this information is as yet unavailable. Our experience has been that the presence of edema-like marrow signal beyond 12 months, or the progressive increase in the quantity of edema-like marrow signal, may herald a poor outcome.

In addition, the influence of factors such as type of chondrocyte cover (periosteum or bilayer collagen membrane), the composition and biomechanics of scaffolds seeded with chondrocytes (MACI, Hyalograft C, etc), and the concentration of growth factors, as well as the patient's age, activity

TABLE 1
Comparative Analysis of Ranges in Parameters During Early-Stage ACI Rehabilitation Protocols[a]

	Patellofemoral		Tibiofemoral	
	Minimum/Earliest Introduction	Maximum/Latest Introduction	Minimum/Earliest Introduction	Maximum/Latest Introduction
Time to full weightbearing	6 h postoperatively	12 wk	7 wk	12 wk
ROM goals for 6 wk postoperatively	30°	120°	90°	130°
Orthoses	No brace	6 wk locked in full extension	3 wk	8 wk in unloader brace
CPM	2 h/d while an inpatient (3-5 d)	8-12 h/d for 6 wk	2 h/d while an inpatient (3-5 d)	6-8 h/d for 6 wk
Patellar mobilizations	Immediately postoperatively	2 wk	Immediately postoperatively	Not included
Hydrotherapy	2 wk	4 wk	2 wk	4 wk
Cycling	4 wk	12 wk	2 wk	12 wk

[a]For studies used, see references 8, 15, 29, 99, 120, 124, 138, 149, 154. ACI, autologous chondrocyte implantation; ROM, range of motion; CPM, continuous passive motion.

level, and local nutrition all seem to be important to graft maturation but are still unclear and unsubstantiated.

Evidence Base

At present, the evidence base for ACI rehabilitation is in its infancy. Prior experience of the evolution of procedures such as ACL reconstruction has shown that where the evidence base for rehabilitation is limited, fears of graft failure are paramount. This concern, in conjunction with the relative minority of therapists with experience treating ACI patients, is likely to be reflected in an overcautious approach to ACI rehabilitation at the present time.

To maximize the benefits of ACI surgery, it is essential for patients to be well informed and educated and for them to adhere to a specific rehabilitation program.[1,2,48] Patient education, the management of patient expectations, and clear goal setting are indispensable within ACI rehabilitation. These values are reliant on a collaborative environment, with good communication between the surgeon, therapist, and patient.

The 2 primary goals for an ACI rehabilitation program are (1) local adaptation and remodeling of the repair and (2) return to function. The rehabilitative challenge is to optimize the achievement of these goals within an individualized and progressive, yet safe, framework. The 3 main components of the rehabilitation program are (1) progressive weightbearing, (2) restoration of range of motion (ROM), and (3) enhancement of muscle control and strengthening.

The repair site is at its most vulnerable during the first 3 months after ACI. At this time, it is important to avoid impact as well as excessive loading and shearing forces. There is a consensus of opinion that weightbearing and ROM should be restricted in early rehabilitation, but there is considerable variation across cartilage repair centers as to the extent and duration of these restrictions, as highlighted in Table 1.

CLINICAL BIOMECHANICS

An understanding of applied clinical biomechanics and an appreciation of the forces and loads that will be exerted on the graft are essential in the design of an ACI rehabilitation program. The contact area (distribution and magnitude), contact load, and contact pressure during rehabilitation should be considered to minimize the danger of damaging the graft and to support the healing process by stimulating the graft physiologically in harmless positions. An extensive review of clinical biomechanics is outside the scope of this article; for a review of patellofemoral and tibiofemoral biomechanics, we suggest referring to McGinty et al,[96] Grelsamer and Klein,[51] and Martelli and Pinskerova.[90] An overview of the pertinent aspects in relation to ACI rehabilitation will now be presented.

BIOMECHANICS OF THE PATELLOFEMORAL JOINT

The patellofemoral joint (PFJ) is a sellar joint composed of the patella and the underlying femoral trochlea. Passive stabilization of the PFJ is created by the femoral condyles, the articular surfaces of the PFJ, the peripatellar retinaculum, and the medial and lateral patellofemoral ligaments.[32,96,134] The primary active stabilizer of the PFJ is the quadriceps muscle group; importantly, the sole dynamic restraint to lateral tracking is the vastus medialis obliquus (VMO).[51,84,96] Although normal functioning and stability of the PFJ are highly dependent on the appropriate balancing of these active and passive stabilizers,[76,96] there are additional influencing factors, including tibial and femoral rotations,[51,76] gluteal muscle status, quadriceps anatomy, femoral trochlea anatomy, tibial tuberosity positioning, and foot mechanics.[51]

TABLE 2
Summary of Patellar Articulation During Knee Flexion and Extension

	Articulation	Contact Area
Full extension	Patella sits above femoral articular surface and rests on supratrochlear fat pad.	No patellofemoral contact with femur.
10°-20°	Initial contact occurs between inferior patella and trochlea.	Joint contact area increases steadily with flexion. Mean contact area at 10° = 126 mm^2; mean contact area at 60° = 560 mm^2.[116]
30°-60°	Middle surface of patella in contact with middle third of trochlea.	
60°-90°	Superior patella makes contact with trochlea.	Contact area remains constant.
90°-135°	Superior patella contact area splits into medial and lateral contact areas that articulate with the opposing femoral condyles.	Controversial—research differs, with contact area either leveling off after 90° or continuing to increase with increasing flexion.[54,81,110,116]
135°	Odd facet of patella contacts medial femoral condyle.	
Full flexion	Lateral femoral condyle fully covered by patella, and medial femoral condyle nearly completely exposed.	

The major function of the patella is to increase the mechanical advantage of the quadriceps mechanism and to minimize the concentration of stress by transmitting forces evenly to the underlying bone. In so doing, the patella allows flexion and extension to be undertaken with reduced quadriceps force, resulting in lower stress across the tibiofemoral joint.[51,76,95] Other functions of the patella are to protect the articular cartilage of the trochlea and the femoral condyles by providing a smooth sliding mechanism for the quadriceps muscle with little friction.[76]

To optimize the distribution of forces and stresses, the patella has a large articulating surface, with the thickest articular cartilage in the human body.[51,76,95] The patellar cartilage shows multiple facets in a pattern that is unique to each individual, and it does not follow the contour of the underlying subchondral bone.[51] The articular surface of the joint is congruent in the axial plane but not in the sagittal plane, and the material properties of the patellar cartilage differ from those in the cartilage of the articulating trochlea.[51,63]

The articulations and contact area at various degrees of knee flexion are pertinent to ACI rehabilitation because of graft location; an overview is shown in Table 2.

The magnitude of the contact area decreases significantly in passive compared to active flexion,[104] whereas the contact area significantly increases with weightbearing.[13] The magnitude of the contact area can also be influenced by tibial and femoral rotations.[76] Men have larger absolute contact areas than do women, but there is no significant gender difference when normalized to patellar dimensions.[13]

The patellofemoral joint reaction force (PFJRF) is equal and opposite to the resultant of the quadriceps tendon tension and the patellar tendon tension.[51,96,152] Thus, the compressive force is a measurement of patellar compression against the femur and is influenced by the knee angle and patellar positioning as well as the quadriceps force.[96,152] With increasing knee flexion, the PFJRF increases, but as it does so, the magnitude of the contact area also increases (Table 2). This increased contact area helps to distribute compressive forces over a larger area, thereby reducing contact stress. Hence, the compressive forces imposed on the patellar articular cartilage have to be considered in the context of the contact area over which they act.[51,96,152] Therefore, PFJ stress is defined as the PFJRF divided by the area of contact between the articular surfaces of the patella and the femur.[152]

The 2 primary goals of ACI rehabilitation are best achieved by optimizing the PFJ contact area rather than decreasing the force,[63,95,96] as this promotes better nutrient exchange of the cartilage[27,63,95] and decreases the pressure on the PFJ.

BIOMECHANICS OF THE TIBIOFEMORAL JOINT

The tibiofemoral joint (TFJ) is a modified hinge joint that has recently been shown to have 6 degrees of freedom: flexion/extension with translation, axial rotation with translation, and varus/valgus angulation with translation.[96,110] Flexion/extension of the TFJ is a combination of rolling and gliding of the articular surfaces, with a spin movement that helps to maintain the joint congruency. During closed kinetic chain (CKC) extension, the femur rolls anteriorly and glides posteriorly on the tibia plateau. In the last 30° of extension, there is a medial rotation of the femur, the "screw home" mechanism. In an open kinetic chain (OKC) extension, the kinematics of the joint is vice versa in relation to the moving tibia. The femoral condyles roll posteriorly and glide anteriorly during flexion in a CKC system, with a conjunct lateral rotation of the femur at the beginning of the movement. In OKC flexion, the kinematics of the joint is vice versa in relation to the moving tibia.

The movement of the lateral compartment differs from that of the medial because of the difference in shape of the femoral condyles. In the medial compartment, the magnitude and distribution of the contact area change because the amount of rolling and gliding is equal. There is no significant change in the contact area in the lateral compartment, as rolling exceeds gliding in a ratio of 1.7 to 1.[58,64,90,110]

The kinematics of the joint is initiated, guided, and limited mainly by the cruciate ligaments but also by muscles and capsular structures. Injury to one of these structures or loss of function leads to altered arthrokinematics, which may be deleterious to the menisci and cartilage.[41,144] During normal activities, the joint contact forces (shear and compressive forces) that are produced are attenuated by several structures of the joint. Shear forces are primarily restrained by the cruciate ligaments. Compressive forces are mostly attenuated by the menisci and the cartilage.[27,63,96] Excessive shear and compressive forces can be deleterious to the menisci and the cartilage. A number of studies have measured these forces[41,110,144,157]; the exact level of musculoskeletal loading is influenced by a number of interindividual factors such as weight, gender, movement coordination, and the activity being undertaken.[144] More pertinently, it is currently unknown at what magnitude compressive and shear forces become injurious to structures such as the menisci and cartilage.[41]

To develop a safe and effective ACI rehabilitation program, shear forces have to be minimized, and the size and location of the defect have to be known because during several activities only parts of the femur/tibia are articulating.[90,110] For example, the posterior aspect of the medial femur condyle contacts the tibia between 90° and 120°[63]; therefore, appropriate loading in positions between 0° and 80° might not be injurious for a graft in this area.

OPEN KINETIC CHAIN VERSUS CLOSED KINETIC CHAIN EXERCISES

In recent years, the clinical use of CKC exercises has increased, as they are assumed to be more functional than OKC exercises.[96] Additionally, CKC exercises have also been shown to involve multijoint action, muscular cocontraction, and a normal proprioceptive input.[51,139] In contrast, OKC exercises have been described as nonfunctional, lacking in joint proprioception and synergistic muscular cocontractions, and producing a decreased joint compressive force component in conjunction with increased joint shear forces.[51,116,142]

To ensure optimal healing of the ACI graft after surgery, peak compressive forces and shear forces should be avoided. A common opinion is that OKC exercises produce higher patellofemoral compressive forces than do CKC exercises and activities.[51,116,142] However, because of the complicated biomechanics of the PFJ, it is not sufficient to solely differentiate between OKC and CKC modes, as the localization of the graft will influence the rehabilitation program. In CKC exercises, the joint reaction force on the PFJ increases as the knee flexes from 0° to 90° and then decreases from 90° to 120°. The CKC exercises are therefore safest in the range from 0° to 45°, especially if the graft is on the proximal aspect of the patella.[28,51] In full extension, there is no patellofemoral contact (Table 2), so straight-leg raises in all positions are safe and produce no abnormal stress on the graft.[28,51] In the OKC exercises, forces are low near full extension (25°-0°) and at 90° of flexion. Extending from this position, the joint reaction force increases until early flexion (25°).[28,51,96] Therefore, OKC exercises are most safely carried out from 25° to 90° of flexion. But as it has already been mentioned, the rehabilitation should be focused on functional activities, and therefore CKC exercises should be emphasized.

Because of the "roll-and-glide" mechanism, the TFJ demonstrates different kinematics between OKC and CKC exercises compared to the PFJ, and this difference results in altered TFJ shear and compressive forces.[96] Excessive tibiofemoral shear forces and compressive forces may be deleterious for the ACI graft. To reduce the risk of abnormal shear forces, one of the most important requirements for ACI are intact cruciate ligaments. Even with functional cruciate ligaments, OKC exercises produce higher tibiofemoral anterior and posterior shear forces than do CKC exercises[40,96]; CKC exercises produce significantly higher compressive forces and increase muscular cocontraction, which lead to greater joint stability. Tibiofemoral shear forces decrease in CKC systems; hence, the risk of damage to the graft is reduced.[96,144]

The selection and progression of CKC and OKC exercises in ACI rehabilitation are dependent on the surgical technique, lesion location and size, concomitant intra-articular injury, healing stage, and patient compliance. The CKC exercises can be performed in a greater ROM, emphasizing functional activities of daily living, but they alone may not provide an adequate stimulus for optimal quadriceps strengthening. Performing OKC exercises in a small ROM increases quadriceps muscle torque and thus leads to better functional outcome. Therefore, rehabilitation after ACI should include both OKC and CKC exercises, with ranges of movement based on the size and location of the ACI graft.

ACTIVE AND PASSIVE MOVEMENTS

Controlled early resumption of activity can promote restoration of function, whereas prolonged immobilization has been shown to delay recovery and adversely affect normal tissues.[25,148] Therefore, mobility after ACI should be rapidly restored. To protect the graft in the early postoperative stage, a short period of partial immobilization is necessary, often with use of orthoses. The duration and degree of partial immobilization are dependent upon the size and localization of the transplanted area.

In conjunction with partial immobilization, restrictions in weightbearing are also generally advocated, although there is considerable variability in the implementation of partial weightbearing (PWB) across cartilage repair centers (Table 1). A particular issue concerns weightbearing recommendations for patellar repairs. In these cases, it can be argued that if a patient is braced in full extension, there will be no contact with the femoral articular surface, and therefore, there will be no need to restrict weightbearing while mobilizing.[51,95,96] When weightbearing restrictions are advised, it is important to check levels of weightbearing on a regular basis and to educate the patient regarding

Figure 1. Assessment of the degree of partial weightbearing for a patient on crutches using a set of scales.

the correct amount of weight. A practical way for the patient to monitor weightbearing is to use a set of weighing scales, as shown in Figure 1.

To enhance the graft healing process, a controlled increase of ROM through passive and active movements is indicated. Repetitive movement intensifies the synovial fluid flow over the repaired site and enhances local diffusion. Moreover, repetitive movement over a significant range induces intermittent changes of intra-articular pressure.[107,112] Several studies report stimulation of chondrocyte activity induced by intermittent pressures.[62,155] Generally, it is thought that the chondrocyte response to mechanical stimulation contributes to the maintenance of the articular cartilage homeostasis. Besides the biomechanical aspects of movement, hormonal factors such as enzymes, growth factors, and cytokines play a key role in reparative signaling for the involved joint cells and structures.[74,83,146] In addition, ROM exercises promote general circulation, can prevent adhesions, and bring relief of pain.[25]

Muscular activity increases both the joint contact area and the joint reaction forces, resulting in the production of higher joint forces with active movements. It is therefore suggested that active movements, in which the ROM implicates high joint reaction forces, should be increased at a slower rate than passive ROM. For instance, after a PFJ repair, knee extension is first introduced passively during ROM exercises, as active knee extension involves quadriceps contraction that results in high compressive forces on the patella.[51,103] To avoid damaging shear forces in the early stages of rehabilitation, active movements of the knee should be performed in a controlled manner. This procedure necessitates a comprehensive program of education and instruction for the patient. First, there is a need for close guidance to ensure correct application of the exercise modality. Second, advice on activities of daily living is essential, as many such activities can provoke excessive shear forces. Good patient understanding and movement control are priorities for optimal care of the healing process in the early stages of rehabilitation.

In summary, active ROM exercises have been shown to be beneficial to increase ROM and to stimulate the healing process.[27,63,150] However, it is imperative that the location and size of the lesion are considered and that the patient progresses through the ROM exercises in a controlled manner.

CONTINUOUS PASSIVE MOTION

Continuous passive motion (CPM) is commonly used in postoperative rehabilitation of knee disorders to minimize the adverse effects of immobilization and to positively influence the healing process. Immobilization of synovial joints results in compositional alterations of articular cartilage: decreased synthetic activity of chondrocytes, decreased proteoglycan content, and reduced water content. In addition, immobilization results in biomechanical changes, including decreased cartilage stiffness and decreased cartilage thickness.[27,63,131,148,150] Generally, immobilization leads to decreased ROM of the joint, followed by an adaptation process of all the articular structures to the immobilized situation. Thus, early mobilization after surgical procedures in synovial joints is advocated to prevent the consequences of immobilization, such as stiffness and adhesions, through passively moving the joint without jeopardizing the healing process.

The biological approach for the use of CPM for cartilage lesions and its positive effects on the healing of full-thickness defects in articular cartilage have been mainly reported by Salter.[129-132] Salter et al[132] described a more rapid metaplasia of the healing tissues within the defect from undifferentiated mesenchymal tissue to hyaline articular cartilage with CPM than with either immobilization or intermittent active motion. Williams et al[153] showed that a period of intermittent active motion followed by CPM may protect and stimulate repair of the articular cartilage matrix. O'Driscoll and Giori[107] proposed the use of CPM as a means to pump blood and edema fluid away from the joint until the swelling no longer develops.

Used postoperatively after periosteal transplantation in patients with full-thickness patellar cartilage defects, CPM shows good results and outcomes, especially compared to the results and outcomes of patients treated only with active motion.[3,82] Postoperative CPM after periosteal transplantation has also shown enhanced cartilage repair tissue that grossly, histologically, and biochemically resembled articular cartilage.[3,108,132] The effect of CPM on ROM is controversial. Investigations comparing CPM with active motion exercise after total knee arthroplasty have not shown any significant difference in the improvement of knee mobility.[11,26,70] However, these studies were based on total knee arthroplasty, and it is unlikely that the results are comparable to ACI.

Continuous passive motion is regularly used in rehabilitation after ACI (Table 1); however, to date, there are no published investigations showing the effects of CPM on graft healing or ROM after ACI. Studies advocate the use of CPM for 6 to 8 h/d to optimize cartilage repair.[16,63,100,136] The ROM in which CPM is performed is dependent upon the size and location of the transplanted area, as it is important to avoid high shear forces that could be detrimental to the graft.

ORTHOSES

Guidelines for ACI rehabilitation frequently mention the use of orthoses (Table 1), which are used to prevent excessive compressive forces over the ACI graft and to facilitate function in the first stages of rehabilitation:

- Postoperative braces can be used to prevent movement ranges. In so doing, they assure that weightbearing is performed in a nonarticulating ROM.
- Functional unloader braces partially unload a specific joint compartment. In addition, some are able to follow the physiological movement of the joint via a specific polyaxial rotation unit.[93]

The recommendation for bracing after a patellar or trochlear repair is generally a postoperative brace (Table 1). In this way, safe ranges of motion can be closely guarded. The maximum length of time that is recommended for bracing patellofemoral repairs is 6 weeks (Table 1).

In terms of bracing for tibiofemoral repairs, there are 2 schools of thought. The first advises initial postoperative bracing for a minimum of 3 weeks, after which an unloading brace can be considered for large uncontained lesions or concomitant osteotomy correction. The second school of thought advises the use of a functional unloading brace right from the outset. Driesang and Hunziker[35] showed high delamination rates of tissue flaps used in articular repair; the functional unloading brace is advocated to prevent early loss of these flaps.[35,67] The maximum length of time that is recommended for bracing tibiofemoral repairs is 8 weeks (Table 1).

ACI AND *PRICES*

The combination treatment of *p*rotection, *r*est, *i*cing (cryotherapy), *c*ompression, *e*levation, and *s*tabilizing is commonly known as the PRICES protocol.[68] The PRICES protocol has a key role to play in immediate ACI postoperative care.

Protection of the operated joint is necessary to prevent graft failure. Protection can be accomplished by patient instruction, close guidance the first days postoperatively, and several rehabilitation modalities.[68]

Relative rest is recommended for the first 48 hours up to 7 days postoperatively.[147] To restore homeostasis, a combination of rest and mobilization is necessary.[68,147] As long as moving around in an upright position induces swelling and pain, bed rest is advised. Mobilizations should be continued.[94,107]

Cryotherapy goals during acute care are to lower tissue temperature, slow metabolism, decrease secondary hypoxic injury, reduce edema formation, facilitate exercise, and speed time to recovery.[71] Cryotherapy facilitates pain reduction by slowing nerve conduction velocity and reducing edema formation.[72] Immediately after knee surgery, there is an increase in intra-articular temperature.[92] However, the temperatures reported postoperatively do not seem to affect chondrocyte viability.[158] Postoperative ice application has been shown to decrease intra-articular temperature[152] and has also demonstrated significantly decreased pain scores and the number of times analgesia is administered.[109]

The rationale for extended postoperative cryotherapy is more questionable. Cooling increases knee joint stiffness and reduces knee joint position sensitivity.[145] These findings are important in ACI rehabilitation programs that involve exercise immediately after a period of cooling. A combination of excessive ice applications and progressive CPM can increase joint stress and could lead to stress-induced hemarthrosis. Because of decreased pain perception, a further disturbance of homeostasis during “forced” passive mobilization is also possible.[147] In the later phases of ACI rehabilitation, cryotherapy may have a positive effect in speeding up the return to participation in sporting activities[60]; however, the relatively poor quality of studies is an objective concern.

Compression is effective in preventing extra-articular swelling.[71] Compression should be applied continuously and evenly with an elastic wrap.

Elevation should be standard practice in postoperative ACI management. Elevation improves venous drainage and hence facilitates the reduction of edema and swelling.[147] The correct level of elevation is for the limb to be above the heart.

Stabilizing the joint allows the local musculature to relax and prevents further injury while allowing wound healing, return of homeostasis, and scar formation.[147]

PROPRIOCEPTION AND NEUROMUSCULAR FUNCTION

Neuromuscular re-education and retraining are critical components in the restoration of functional joint stability, yet they are often undervalued within the rehabilitation program. Neuromuscular function broadly involves the detection of afferent input via mechanoreceptors: the processing of a response to the stimulus in the central nervous system and the initiation of an efferent reaction to maintain balance, stability, and mobility.[77] Rehabilitation can assist in the restoration of proprioception, but high-level studies are scarce.[57,75,78]

Proprioceptive deficits in the knee have been observed in conjunction with a number of common injuries and surgical interventions, including osteoarthritis (OA),[12,61,135] patellofemoral pain syndrome (PFPS),[9] before and after ACL reconstruction,[10,45,46] and total knee arthroplasty.[7,47] Interestingly, it would seem that proprioceptive loss after injury, surgery, or joint degeneration is not localized to the affected joint. Studies looking at proprioception between operated and nonoperated legs,[47,125] OA and non-OA knees,[135] and ACL-injured and non–ACL injured knees[119] have found reduced proprioception in the contralateral unaffected limb as well as the expected reduction in the affected limb.

Currently, there are no published studies that have researched preoperative and postoperative proprioception and neuromuscular control in patients with local articular cartilage damage of the knee. However, the mere fact that a surgical intervention has taken place will mean that there will be some degree of proprioceptive loss postoperatively.[61,81] It is also likely that open procedures result in a greater degree of proprioceptive loss than do arthroscopic procedures because of an increased level of disruption to joint mechanoreceptors.[45,56] The effects of the size and location of an articular cartilage lesion on proprioception are not known. Moreover, the influence of symptom duration on a patient's preoperative level of proprioception as well as the postoperative time needed and potential for full restoration are in question.

It is important for the ACI rehabilitation program to address proprioceptive and quadriceps activation deficits in a dynamic, functional manner. Quality of neuromuscular control should be a main feature throughout the rehabilitation program. Three windows of opportunity exist for the ACI patient to address proprioceptive losses, and these present in the preoperative stage, between the arthroscopic biopsy and the ACI surgery, and after surgery. Neuromuscular rehabilitation needs to be adequately addressed in each of these stages. Current ACI rehabilitation guidelines generally do not cover neuromuscular rehabilitation sufficiently, or they even exclude this important area of rehabilitation altogether.

The focus of neuromuscular-control rehabilitation is the retraining of coordination patterns via feedback and feed-forward control systems in a functional, dynamic, and progressive manner. This process involves varying movement speed from slow movements that target the feedback system in the early stages of rehabilitation through progressions to fast movements that focus more on retraining the feed-forward system in the later stages of rehabilitation. The exercises should be performed throughout the full available ROM and should ideally be performed on both the affected and the nonaffected limbs because of the likely decreases in proprioception in the contralateral limb.[47,119,125,135]

Specific exercises for neuromuscular rehabilitation after ACI should be addressed on an individual basis in line with any weightbearing or ROM restrictions that may be in place. Generally, proprioceptive challenges tend to be introduced through balance training and progressed in the following ways:

- 2-legged to 1-legged stance;
- eyes open to shut;
- slow to fast movements;
- introduction of unstable base (eg, mats, unidirectional/multidirectional wobble boards, trampet, and gym balls) (Figure 2);
- introduction of resistance and/or center of gravity shift (eg, from light to heavy elastic resistance band);
- introduction of distractions (eg, throwing, catching, reaching, turning); and
- introduction of sport- and occupation-specific drills.

In addition, it is essential that more functional, dynamic tests are incorporated into the rehabilitation program. These tests involve working with the patient on the quality of his or her neuromuscular control in activities such as descending stairs, gait, rising from chairs, and in the later stages, running, hopping, and jumping.

Figure 2. Example of bipodal proprioception exercise using an inflatable disc.

HYDROTHERAPY

Exercises in water allow early active mobilization and early loading and improve neuromuscular performance, especially during the initial phase of a rehabilitation program.[118] The reduction in gravity under water decreases the detrimental effects of weightbearing and the impact forces on joint structures during movement,[117,118] enabling ROM exercises to be performed in a functional position with a reduced risk of high shear forces under compression. Factors such as water depth and flow will also influence the loading demands on the knee joint, so it is important to base the rehabilitation program on the general principles of hydrotherapy.

Exercises under water produce lower EMG activity during isometric and dynamic conditions when compared to similar exercises on dry land,[118] and therefore, joint forces are lower. For this reason, hydrotherapy in ACI rehabilitation, including strengthening, proprioception training, and functional activities, is beneficial. Investigations show that an early and intensive application of hydrotherapy for improving coordination and strength during rehabilitation is advisable.[44] In addition, moving in water endows the patient with a "feeling of freedom," as they can walk without crutches and move around without restriction. This is an important psychological advantage.

MANUAL THERAPY AFTER ACI

Two conceptual approaches to manual therapy need to be mentioned within ACI rehabilitation: the clinical investigation and the application of manual techniques to re-establish physiological regulation. The ability to define passive movement disorders in a joint, the localization of swelling, the involvement of anatomic structures, temperature, and so on, are not only necessary for good clinical practice but also for a comprehensive tailoring of the rehabilitation.[147] Manual therapy as an independent application of manual techniques for general knee disorders is questionable. However, the combination of manual therapy with exercises and specific manual techniques for the enhancement of ROM prove to be more effective than exercises alone.[33,106] Manual therapy is often cited as being used to facilitate the restoration of local function, and ACI rehabilitation protocols often mention gentle manual mobilization techniques to prevent parapatellar soft tissue formation (Table 1). Few references are made in the protocols to specific techniques to facilitate accessory movements, as in the use of passive anterior glides to the tibia[8] or lateral rotation of the tibia where there is a limit to TFJ extension, although they prove to be effective in facilitating immediate muscle control.[31,61]

ELECTROTHERAPEUTIC MODALITIES AND EMG BIOFEEDBACK

The role of electrotherapeutic modalities in postoperative ACI rehabilitation is controversial. In the first few weeks after ACI, rehabilitative exercises are often difficult to perform, not only because of edema and pain but also as a result of the joint receptor feedback disruption that is an inevitable consequence of surgical intervention. The proposed therapeutic benefits of electrotherapy include pain reduction, increased ROM, reduced edema, enhanced voluntary muscle recruitment, and the promotion of cartilage healing. However, research remains limited and is often restricted to animal studies, and to date, the effect of electrotherapy on chondrocytes and their maturation in vivo is largely unknown.

Therapeutic Ultrasound and Laser

Low-intensity pulsed therapeutic ultrasound (TUS)[30,36] and low-level laser therapy[86,127,133] have been proposed as providing appropriate stimuli for the acceleration of chondrogenesis. However, it has yet to be demonstrated that these therapies can stimulate articular cartilage regeneration in vivo.

Interferential Therapy

Interferential therapy (IFT) has been shown to have significant effects in reducing postoperative pain, increasing ROM, and reducing edema after knee surgery.[65] However, there are issues regarding functionality, efficiency of therapy time, and clinician dependence.

Transcutaneous Electrical Nerve Stimulation

The effectiveness of transcutaneous electrical nerve stimulation (TENS) as a pain-relieving modality has been studied in a range of populations with variable outcomes. On one hand, several studies have found TENS to be effective in decreasing pain after knee surgery,[6,66] but other studies have found no significant benefit in pain reduction.[20] A review of the role of TENS concluded that it had no place in the treatment of acute postoperative pain, as it was not an effective analgesic.[97]

Arthrogenic muscle inhibition (AMI), and specifically quadriceps inhibition after knee surgery, has been well documented.[143,156] Recovery of voluntary control of quadriceps function is an important aspect of ACI rehabilitation and should be addressed as early as possible after surgery with isometric quadriceps setting exercises. Transcutaneous electrical nerve stimulation has been proposed as a treatment modality for AMI on the basis that it competes with the type 1 afferent nerve fibers that carry the mechanoreceptor feedback. One study has shown a small increase in voluntary quadriceps activations after TENS in knee surgery patients,[6] but a more recent study found that TENS failed to disinhibit vastus medialis and decrease AMI after knee joint effusion.[59]

Neuromuscular Electrical Stimulation

An alternative strategy to address AMI utilizes the production of involuntary muscle contractions by neuromuscular electrical stimulation (NMES) (Figure 3). Neuromuscular electrical stimulation has been found to be effective in reducing quadriceps extensor lag[49] and in strengthening

Figure 3. The use of neuromuscular stimulation to produce isometric involuntary muscle contraction.

TABLE 3
Overview of the Key Biomechanical Features of Cycling and Rowing Exercise Modalities

Cycling Ergometer	Rowing Ergometer
Nonweightbearing/low impact	Nonweightbearing/low impact
Sagittal plane	Sagittal plane
Closed kinetic chain exercise	Closed kinetic chain exercise
Unilateral leg action	Bilateral leg action
Mean range of knee flexion 30°-110° in 1 pedal revolution	Mean range of knee flexion 0°-130° in 1 rowing stroke
Minimum 100° of knee flexion required	No minimum degree of knee flexion required
Maximum knee flexion controlled by saddle height	Maximum knee flexion controlled by length of slide
High repetitions per minute (60-90 rpm)	Low repetitions per minute (16-30 spm)

the quadriceps after knee arthroplasty[140] and ACL reconstruction.[43] However, it is important to note that voluntary muscle strengthening has been found to be just as effective as NMES.[80,111] We therefore suggest that NMES is a useful adjunct to the primary exercise program in ACI rehabilitation and acknowledge that there may be an increased role for NMES in those patients who are poorly motivated, have long-term muscle weakness, and/or are slow responders.

EMG Biofeedback

Electromyographic biofeedback has been used as a tool to re-educate patients in voluntary quadriceps contraction through the provision of feedback about the quality of their muscle contraction. Results have shown that EMG biofeedback used with muscle strengthening enhances quadriceps recruitment after arthroscopy,[79] arthroplasty,[141] and ACL reconstruction.[34]

EXERCISE MODALITIES

There is currently no ACI-specific evidence base to directly support the frequency, intensity, type, and timing of exercise modalities during rehabilitation. Recent studies have advocated the avoidance of certain ranges of knee movement, for example, active knee flexion between 40° and 70° in the early stages after patellofemoral ACI.[24] However, virtually all exercise modalities, including common activities such as walking, cycling, and rowing, involve a knee flexion/extension pattern within this range.

The incorporation of exercise modalities into ACI rehabilitation programs may be better considered in terms of minimizing joint stress as opposed to the complete avoidance of specific ranges of movement. This result can be achieved through the selection, introduction, and progression of exercise modalities that are appropriate for the graft age, size, and location. An understanding of the variations in the magnitude and direction of loads at the knee and the knee flexion angle at which the peak load is exhibited is therefore required for each proposed exercise modality. Exercise modalities should complement but not replace functional movement retraining (eg, stairs).

Cycling

In comparison with other activities of daily living such as walking or stair climbing, the maximum load-moments on the knee joint in cycling are small.[37] An overview of the pertinent biomechanical features of cycling is presented in Table 3. Increases in the cycling workload result in a significant increase in knee load-moments and compressive and shear forces, but increases in the pedaling rate do not appear to affect the maximum knee load-moment.[37] It is therefore possible to introduce stationary cycling at an early stage as long as resistance is minimal and there is sufficient ROM to allow a complete pedal revolution (Table 3).

Along with the correct selection of resistance, another important factor in cycling that needs to be considered is saddle height because of its direct influence on knee flexion angles, as shown in Figure 4.[37] If the saddle height is too low, increased PFJRFs occur,[38] especially if combined with too high a gearing; TFJ load-moments decrease with increasing saddle height.[39] Too high a saddle height, often as a consequence of insufficient available range of knee flexion, results in frontal plane rocking from the pelvis and hip, which is unfavorable for rehabilitation in terms of control and muscle activation patterns. High saddle heights are a predisposing factor for an increased risk of developing iliotibial band friction syndrome (ITBFS), especially if knee ROM is not full.[42] An increase in saddle height for a short postoperative period is unlikely to significantly predispose a patient to ITBFS because the condition is predominantly due to overuse. However, if the saddle height is increased to initially accommodate restrictions in knee ROM, then it is important to normalize the saddle height in parallel with the restoration of knee ROM to reduce the future risk of problems such as ITBFS.

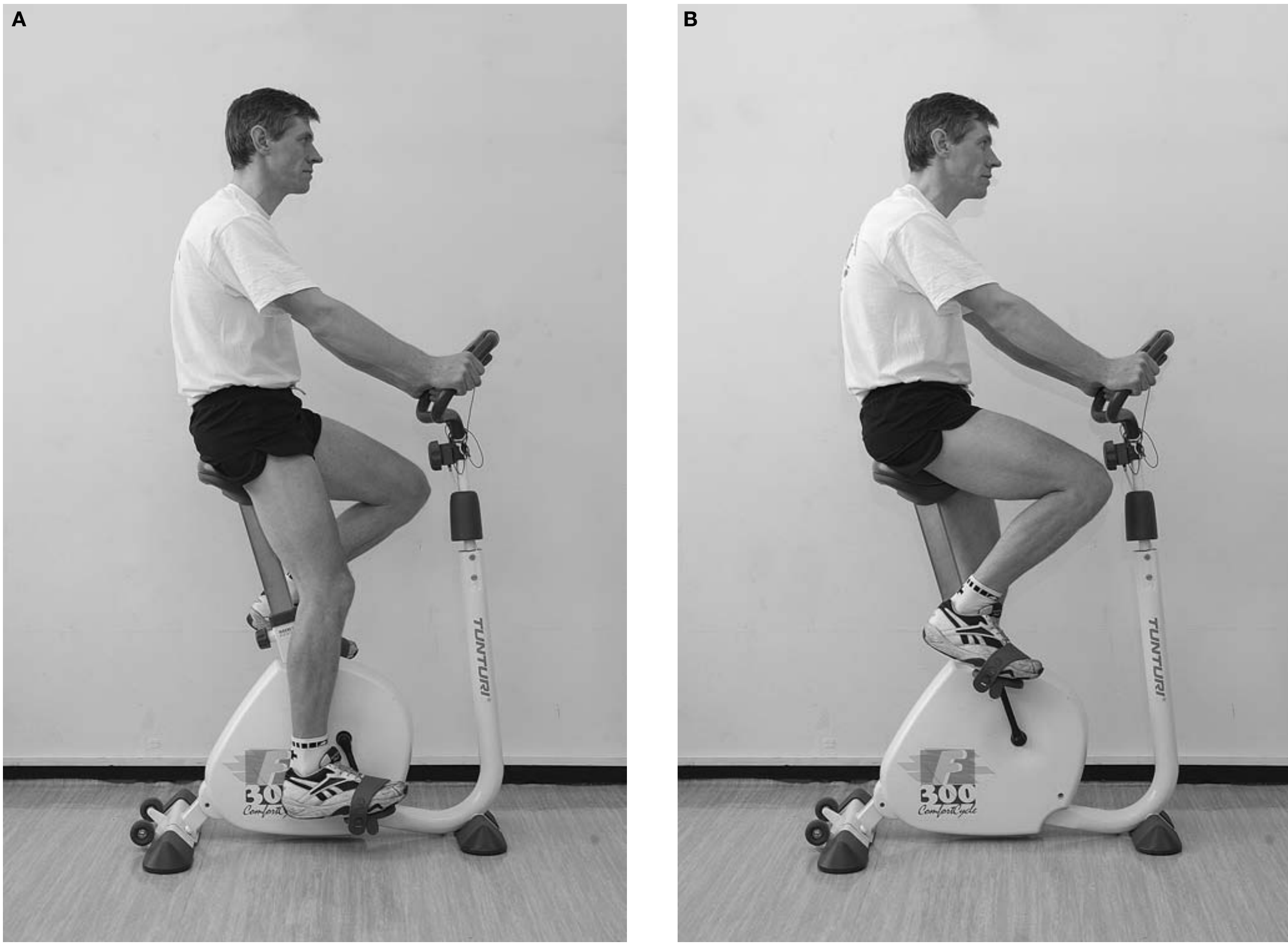

Figure 4. Stationary cycling showing range of knee flexion from bottom dead center (A) to top dead center (B) at correct saddle-height positioning.

Analysis of the effect that changing the direction of pedaling has on knee joint biomechanics has shown that reverse pedaling requires quadriceps muscle activity in ranges of greater knee flexion compared with forward pedaling[22] and that the vastus medialis is more active in reverse pedaling.[22] Tibiofemoral compressive loads have been shown to be lower in reverse pedaling, especially near peak extension of the knee.[105] However, PFJRFs have been found to be significantly higher in reverse pedaling compared with forward pedaling.[21,105] On the basis of this evidence, reverse pedaling may be considered for TFJ rehabilitation to reduce loading on the knee but should not be advocated for PFJ rehabilitation because of the increases in loading on the knee joint.

Recumbent Cycling

Recumbent cycling is an increasingly common activity in gymnasiums and fitness centers. Overall, general muscle moments are similar between upright and recumbent cycling, but importantly, the magnitudes of the general muscle moments at low workloads are lower during recumbent cycling.[50] This condition is due to the body being in a position in which the hip can apply a greater extensor moment than the knee in the power phase of the pedal revolution at low workloads.[50] Proportionally, the amount of work done by knee flexion is significantly higher in recumbent cycling compared with upright cycling.[122] Reiser et al[121] found no changes in the tension/compression forces at the knee but did find that posterior shear forces were significantly reduced in recumbent cycling. These findings indicate that recumbent cycling is a useful exercise modality in ACI rehabilitation and that there may be advantages in using recumbent cycling as a progression or alternative to upright cycling.

Rowing Ergometer

Similarities exist between cycling and rowing (Table 3) that support the inclusion of rowing as an exercise modality for lower limb rehabilitation. However, there are differences between the 2 exercise modalities that have implications for ACI rehabilitation program design. In cycling, knee flexion has to be 100° before a full pedal revolution can be achieved; in contrast, there is no such biomechanical constraint in rowing. Rowing has a number of distinct advantages over

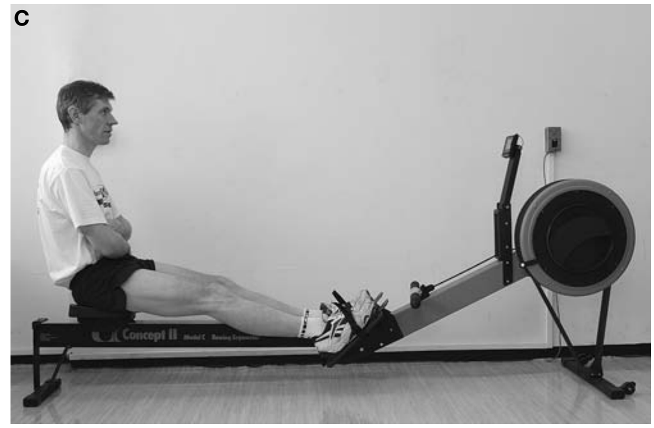

Figure 5. Ergometer rowing without using a handle at (A) the start of drive, (B) mid-drive, and (C) the end of drive.

cycling: active flexion and extension in the ACI limb can be assisted by the non-ACI limb, there is greater proximal stabilization, and loads are applied bilaterally. The relatively slower movement speed of the rowing action facilitates improved neuromuscular control for early-stage rehabilitation, but the higher movement speed of cycling is likely to be more of an advantage in later-stage rehabilitation. Anecdotally, rowing tends to be introduced at a later stage in ACI rehabilitation than is cycling (Table 1), but it is often introduced as a full-range, unrestricted activity.[8,124] With adequate attention to the minimization of joint stress via stroke rate and pace guidance, "no handle" ergometer rowing could be introduced earlier than stationary cycling and could feasibly be utilized as an "active" progression after CPM (Figure 5).

Other Exercise Modalities

Other low-impact exercise modalities commonly available in fitness centers include elliptical trainers, cross-trainers, ski trainers, and stair climbers. These modalities have the advantage of being CKC activities; however, clinical biomechanical data are limited, and the implications for loading on the knee joint are not fully understood. A major consideration is the potential lack of synchronization between the hip and knee joints that could increase the transfer of forces to the knee and subsequently increase the stress that is placed upon the knee joint.

Whole-body vibration, in which the patient undergoes a sensory bombardment, has recently become a popular training modality for gaining strength.[126] However, the lack of research concerning cartilage tissue repair, the overload in a sustained exercise position, and the exact effect of different training parameters are all reasons for not implementing whole-body vibration in the early stages of rehabilitation after ACI at this time.

RETURN TO SPORT AFTER ACI

Rehabilitation after ACI is widely recognized as being lengthy, with maximum improvement in knee symptoms taking as long as 3 years after surgery.[69] This is a pertinent factor to consider because of the level of impact that the duration of the rehabilitation has on the time out of sport. Only 1 multicenter study to date has researched return to sport after ACI.[101,102]

Mithöfer et al[101,102] studied the ability of 45 soccer players to return to soccer in a 40-month (±4 months) follow-up period after ACI. They found that despite 72% of players reporting good to excellent knee function, only 33% were able to return to soccer.[101,102] What is unclear is whether the two thirds of players who did not return to soccer were clinically unable to return to play or whether they either chose to switch to a lower-impact activity or opted not to return to sport at all. The definition of "ability to return to sport" and the relevance of current outcome measures to sporting participation require further exploration and clarification. Younger age and shorter preoperative duration of symptoms were also shown to significantly improve the ability to return to soccer.[101,102] However, this improved potential to return to soccer could well be due to a greater influence of psychosocial factors and changing life priorities rather than to physiological properties such as healing and chondrocyte maturation.

Bowen et al,[16] in their article on return to play after chondral injuries to the knee, highlighted the fact that the success of rehabilitation is multifactorial and recognized that psychosocial factors such as patient motivation were important contributors. Drawing heavily on self-determination theory, it is proposed that the type of motivation for returning to sport (internal vs external) is an important factor, not only in determining whether the athlete does return but also in the outcome of the return.[115] Recent studies that have considered re-entry into sport after career-threatening injuries have shown that reinjury concerns are significantly implicated in the prevention of an athlete returning to sport[73,115] (N. Walker, unpublished data, 2005). Emotional response to athletic injury should be considered in connection with return-to-sport goals for ACI patients, both preoperatively and postoperatively.

After total knee replacement, advice to patients that high-impact activity may jeopardize their surgery outcomes can result in changes in postoperative activity.[17] Consideration of the impact that advice from the surgeon, therapists, other patients, significant others, and general information sources may have on postoperative activities is an important factor that is underrecognized and poorly evaluated.

With the uncertainties that surround ACI rehabilitation at present, the general consensus of opinion among cartilage repair centers appears to be that ACI surgery should be targeted on the reduction of symptoms and on improving functional daily activities rather than as a method of returning to high-level sports participation for competitive athletes with chondral damage. General recommendations are that low-impact sports and exercise such as swimming, cycling, and golf can usually be resumed within 6 months.[8,15,120,124,138,149] Recommendations for timescales for a return to higher-impact activities such as racquet sports, team sports, martial arts, and running range from an earliest postoperative return at 12 months up to 18 months.[#] However, there is considerable variation between people, so return to sports after ACI should be based on the key criteria that

- the patient's graft is able to withstand the specific demands of their chosen sport, and
- the patient has been rehabilitated to a point at which they are able to safely return to sports involvement.

Where a return to sport is planned, it is important that sport-specific activities are included as functional progressions within the rehabilitation program.

ACI REHABILITATION PROGRAMMING

Rehabilitation after ACI is a process and, as such, the staging and progression of individual rehabilitation elements need to be considered with respect to the primary goals of local adaptation and remodeling of the repair and of return to function. A generic ACI postoperative rehabilitation program based on the current understanding of the biology of graft healing and on the corresponding therapy goals, modalities, and criteria for progression has been proposed by us and is shown in Table 4. Time frames have been indicated, but we do not recommend the adoption of a rigid timetable, as the proposed phases are not mutually exclusive, and considerable variation exists between people. Modifications to the rehabilitation program may be necessary based on defect size, location, age, previous activity level, concomitant surgical procedures, and

[#]References 8, 15, 29, 99, 120, 138, 149.

TABLE 4
Postoperative Timelines for ACI Rehabilitation Based on Biology of Healing and Corresponding Therapy Goals, Modalities, and Criteria for Progression[a]

PHASE I: RECOVERY AND PROTECTION (WEEKS 0-4)

Biology: cell attachment, inflammation, and proliferation

Therapy goals
- Protect healing tissue from load and shear forces and allow cell adherence
- Restore joint homeostasis (for relative rest situation)
- Prevent adhesions
- Restore full passive knee extension
- Gradually increase pain-free knee flexion
- Ensure safe transfers at home and for transportation
- Regain quadriceps control

Modalities
- Education/coaching
- Cryotherapy, elevation, and compression
- Continuous passive motion
- Active ROM exercises (joint circulation exercises: ankle pumps, heel slides, hip extension and abduction)
- Weightbearing control with crutches for ADL
- Bracing (postoperative or functional unloading) as indicated
- Quadriceps setting
- Patellar mobilization
- Biofeedback and electrical muscle stimulation as indicated

Criteria for progression to next phase
- Minimal pain and swelling, able to perform daily joint circulation exercises
- Surgical incisions healed
- Full passive knee extension and voluntary quadriceps activity
- Active, pain-free knee flexion of 90°
- Earliest time for progression to next phase: 4 weeks postoperatively

PHASE II: INAUGURATION (WEEKS 4-8)

Biology: cell differentiation and start of maturation phase

Therapy goals
- Restore joint homeostasis (for daily joint circulation exercises)
- Increase pain-free ROM (local stretching of the joint capsule is acceptable)
- Maintain full extension
- Ensure safe transfers at home and for transportation
- Gradually increase weightbearing for protection of repair
- Gain quadriceps control in safe, multiangle CKC exercises

Modalities
- Education/coaching
- Active ROM exercises (joint circulation exercises: heel slides, stationary rowing [no resistance], or bicycle [minimal resistance])
- Balance for control of weightbearing for ADL (with brace if indicated)
- Continued bracing (postoperative or functional unloading) as indicated
- Quadriceps isometric multiangle control and coordination
- Quadriceps setting

(Continued)

TABLE 4
(Continued)

- Gluteus maximus, medius, and minimus retraining
- Patellar and soft tissue mobilization
- Biofeedback and electrical muscle stimulation as indicated
- Hydrotherapy for gait coordination and joint circulation exercises

Criteria for progression to next phase
- Minimal pain and swelling and voluntary quadriceps activity
- Full passive knee extension
- Active, pain-free knee flexion of >110°
- Ability to perform daily joint circulation exercises for at least 30 minutes within homeostasis
- Earliest time for progression to next phase: 6 weeks postoperatively

PHASE III: MATURATION (WEEKS 8-12)

Biology: cell differentiation and maturation

Therapy goals
- Restore joint homeostasis (for light functional exercises)
- Gain full, active, pain-free ROM (local stretch of the joint capsule is acceptable)
- Ensure safe transfers at home and for transportation
- Gradually increase weightbearing for protection of repair
- Increase quadriceps strength in safe, multiangle CKC exercises
- Regain quadriceps control in FROM CKC exercises
- Gradually increase ADL
- Regain optimal coordination for walking, stair climbing/descending, and transfers

Modalities
- Education/coaching
- Active ROM exercises (no resistance over repaired zone and light resistance in safe ranges)
- FWB control in exercise conditions (balance, mat, sport- and occupation-specific)
- Weaning off bracing and/or crutches
- Feed-forward exercises for coordination in multidirectional tasks
- Quadriceps settings
- Gluteus maximus, medius, and minimus retraining and strengthening
- Patellar and soft tissue mobilization
- Biofeedback and electrical muscle stimulation as indicated
- Hydrotherapy for gait coordination and endurance

Criteria for progression to next phase
- Minimal pain and swelling
- Full passive knee extension and voluntary quadriceps activity
- Active, pain-free knee flexion of >110°
- Able to walk 1-2 miles or stationary bicycle/rowing (light resistance) for 30 minutes within homeostasis
- Earliest time for progression to next phase: 10 weeks postoperatively

PHASE IV: INTEGRATION (WEEKS 12-26)

Biology: maturation and integration

Therapy goals
- Restore joint homeostasis (for intense low-impact exercises)
- Ensure safe static postures

(Continued)

- Increase lower-limb strength through FROM in CKC
- Gradually increase training load and volume
- Maintain joint circulation exercises (3 or more times/wk)

Modalities
- Education/coaching
- Active ROM exercises with light resistance in safe ranges
- Balance exercises in challenging postures (balance, trampoline, flip boards, sport- and occupation-specific)
- Feed-forward and feedback exercises for coordination in multidirectional open tasks
- Hydrotherapy for gait coordination and endurance
- Strength training (light resistance over repaired zone and full resistance over other areas)

Criteria for progression to next phase
- No pain or swelling after intense low-impact exercises
- Full, pain-free ROM
- Able to perform daily joint circulation exercises for at least 60 minutes within homeostasis
- Earliest time for progression to next phase: 12 weeks postoperatively

PHASE V: FUNCTIONAL ADAPTATION (WEEKS 26-52+)

Biology: maturation and integration

Therapy goals
- Restore joint homeostasis (for impact exercises longer than 30 minutes)
- Ensure safe dynamic postures
- Aim for unrestricted ADL
- Gradually increase lower-limb strength in range of repair (OKC and CKC)
- Maintain training intensity, load, and volume
- Maintain joint-circulation exercises (daily)
- Prevent future damage/injury
- Continually improve comfort and confidence in knee

Modalities
- Education/coaching
- Active ROM exercises: light resistance, full range
- Balance exercises in challenging, coordinative tasks (balance, trampoline, flip boards)
- Hydrotherapy for general endurance
- Sport-specific agility training (unidirectional, noncontact)
- Strength training (full resistance over repaired zone)

Criteria for progression to next phase
- No pain or swelling after impact exercises longer than 30 minutes
- Full, pain-free ROM
- Graft is able to withstand the specific demands of the activity, as assessed by sport-specific functional testing
- Patient is motivated to return to sport
- Earliest time for progression to next phase: 26 weeks postoperatively

PHASE VI: RETURN TO SPORTS (WEEKS 26-78+)

Biology: maturation and integration

Therapy goals
- Restore joint homeostasis (for specific sports activities)
- Maintain safe dynamic postures
- Aim for unrestricted sport (at same or lower level)
- Restore symmetry, including lower-limb strength and flexibility

(Continued)

TABLE 4
(Continued)

- Increase training intensity, load, and volume
- Prevent further damage/injury
- Restore confidence in knee
- Restore competition fitness

Modalities
- Education/coaching
- Active ROM exercises: unrestricted resistance, full range
- Sport-specific agility training (multidirectional, contact)
- Balance exercises in challenging, sport-specific coordinative tasks
- Hydrotherapy for cardiovascular fitness
- Pre-sports conditioning (circuits)
- Functional strength training

Criteria for progression to increased work load
- No pain or swelling after specific sports activities
- Full, pain-free ROM
- Graft is able to withstand the specific demands of the sport
- Earliest time for return to sports: 26 weeks postoperatively for lower-impact activities and 52 weeks postoperatively for higher-impact activities

[a]ACI, autologous chondrocyte implantation; ROM, range of motion; ADL, activities of daily living; CKC, closed kinetic chain; FROM, full range of movement; FWB, full weightbearing; OKC, open kinetic chain.

individual patient demands.[8,63,154] Progression should not be totally dependent on postoperative time; it is more important that goals are reached at the end of each phase. Effective individual patient programming is reliant on good patient education and on regular, informative communication between all members of the rehabilitation team.

FUTURE DIRECTIONS

Although research focused specifically on rehabilitation after ACI is in its infancy, the patient demand for rehabilitation after ACI surgery is a growth sector, with the international expansion of orthopaedic centers offering ACI as a cartilage repair technique. Current ACI rehabilitation is heavily influenced by the fact that the procedure consists of 2 stages, culminating in implantation of cultured autologous chondrocytes via open arthrotomy. The protection of the ACI graft from deleterious forces is further complicated by the lack of definitive research on the stress necessary to disrupt or delaminate the graft.

With the progression of understanding into chondrocyte senescence comes the increasing viability for the utilization of composite ACI techniques for the surgical management of moderate OA.[91] In the near future, this biological alternative could offer significant benefits to the conventional treatment options of tibial osteotomy and partial knee replacement. The evolution of all-arthroscopic techniques will have a significant impact on rehabilitation and should reduce the surgical morbidity associated with open arthrotomy. In addition, developments in novel scaffolds and in vitro chondrocyte maturation before implantation would significantly reduce the inherent fragility of the ACI graft during the early postoperative stage. In the future, is it is likely that it will be possible to "accelerate" ACI rehabilitation programs to reflect these developments in orthopaedic tissue engineering. However, to optimize ACI rehabilitation for the benefit of future patients, there is an urgent need for further studies to form the foundations of the evidence base for ACI rehabilitation.

Until the time an evidence base is available, clinicians involved in ACI rehabilitation will have to continue depending on knowing precise surgical details (defect location and size and concomitant procedures) and to have an understanding of chondrocyte maturation, clinical biomechanics, and the principles of exercise programming and functional progressions. Such knowledge requires the adoption of a coordinated approach between basic scientists, surgeons, and therapists.

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