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Title: Accuracy of Partial Weightbearing after Autologous Chondrocyte Implantation

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Accuracy of Partial Weightbearing After Autologous Chondrocyte Implantation

Objective(s): To determine whether patients can accurately replicate and retain weightbearing (WB) restrictions in both stationary (static) and dynamic conditions following autologous chondrocyte implantation (ACI).

Design: Case series.

Setting: Rehabilitation clinic.

Participants: A consecutive sample of 48 patients who had undergone ACI to a medial or lateral femoral condylar defect in the knee.

Intervention(s): Patients were trained to partially weightbear using bathroom scales and forearm crutches prior to assessment.

Main Outcome Measures(s): A force platform was used to measure peak vertical ground reaction forces in patients during static and dynamic conditions immediately after WB instruction and training, and again during gait 7-days after training.

Results: Immediately after instruction and weightbearing practice on a set of scales, patients exerted a mean of 15.8% body weight more than expected during walking for 20% WB trials, 8.3% more for the 40% trials, 11.9% more for the 60% trials, and 1.2% under the prescribed 80% trials. Accuracy of WB replication improved across all WB levels when assessed 7-days later, whereby patients exerted a mean of 6.6% body weight more than expected during walking for 20% WB trials (9.2% body weight improvement), 4.2% more for the 40% trials (4.1% body weight improvement), 9.9% more for the 60% trials (2.0% body weight improvement), and 0.2% more for the 60% trials (1.0% body weight improvement).

Conclusions: Patients were unable to follow WB restrictions after instruction and practice on a set of scales, and patients were unable to replicate WB levels in both static and dynamic conditions.

Keywords: partial weight bearing accuracy, rehabilitation, autologous chondrocyte implantation.

Autologous chondrocyte implantation (ACI) has shown early clinical success as a repair procedure to treat focal articular cartilage defects in the knee.^{1,2,3,4} The general ACI procedure involves isolating and culturing a patient's own chondrocytes in vitro and reimplantation of those cells into the cartilage defect; therefore, over time, development and remodeling of the repair tissue into hyaline-like cartilage can occur. Postoperative rehabilitation after ACI involves a gradual and progressive program that emphasizes full motion, controlled exercises, and progressive load-bearing.² Partial weightbearing (PWB) throughout the early stages after ACI is encouraged⁵ to provide protection and progressive stimulation of cells, without overloading the graft; however, it is unknown whether patients can replicate these desired loads, potentially hindering optimal short- and long-term development of the repair tissue.

Robertson et al⁶ proposed rehabilitation should consist of a structured load-bearing program progressing from 20% to 100% body weight (BW) over a 3- to 4-month postoperative period. Numerous methods exist for teaching this progressive PWB program to patients, including verbal instruction,⁷ pressure applied to the hand of a licensed physical therapist,⁸ the use of standard bathroom scales,^{5,8,9,10,11,12,13,14} "limb load monitors"¹⁵ or pressure insoles,^{16,17} and force monitoring platforms.⁸ The bathroom scale method is recognized as one of the most common and practical methods of teaching PWB.⁵ However, mixed results surround the evaluation of this method as an effective tool for teaching PWB, whereby both good^{10,12} and poor^{8,9,13,14,17} PWB replication ability has been reported.

A number of issues arise pertaining to the use of PWB for ACI rehabilitation. First, unidirectional loading in a stationary position fails to reproduce the situation experienced during

dynamic gait⁸ whereby body and limb accelerations are introduced. Second, the patient must not only be able to replicate the prescribed PWB levels accurately after instruction, but also to retain that information over an extended period. Third, much of the existing research has explored PWB ability at only one nominated weightbearing (WB) level,^{8,9,10,11,12,17,18,19} and in unaffected subjects.^{8,9,10,11,12,13,17,18} Factors in patients such as pain⁹ and reduced muscle power²⁰ affect PWB ability, as may an altered mental state and fragility after the operative procedure.

Presuming a direct relationship between ground reaction force (GRF) experienced at the feet and loading experienced at the articular surface, the purpose of graduated PWB in ACI rehabilitation is to provide both protection and an ongoing stimulus to developing repair tissue. Postoperative rehabilitation for the ACI procedure focuses on increasing load-bearing in gait over time, which provides the optimal stimulus for developing chondrocytes at each postoperative stage, without overload, and possible de-lamination of the graft. The accuracy of load-bearing replication and retention during PWB gait throughout the duration of the rehabilitation program is based on the ability of each individual patient to learn, replicate, retain, and exhibit the desired loads while walking. However, it is unknown whether patients can actually attain this theoretical program.

Our first two hypotheses were that patients undergoing ACI could not replicate vertical GRF loading within 5% of patient BW in both static and dynamic conditions immediately after instruction, across a range of PWB loads throughout the rehabilitation period. Thirdly, we hypothesized patients could not replicate these loads within 5% of patient BW dynamically after a 7-day instruction-retest interval, and fourthly, that there would be no significant improvement

over the 7-day period across all PWB loads. Fifth and finally, we hypothesized patients undergoing ACI who were poor at replicating vertical loads in a static condition were also poor at replicating those loads during walking.

Methods

We instructed 48 patients (31 men, 17 women) who had undergone ACI to the knee how to achieve PWB loading at 20%, 40%, 60%, and 80% of their individual BW using the bathroom scale method. After instruction and practice of each of the nominated WB levels, the ability to replicate the nominated loads within 5% of BW in both a stationary (static position - a situation that duplicated the practice setting) and during walking using a force platform was assessed. This assessment took place both immediately (static and dynamic) and 7 days after instruction (dynamic).

Patients who had undergone ACI to localized, full-thickness medial or lateral femoral condylar defects (less than 10 cm² on MRI) to the knee participated in this study. Patients with multiple articular cartilage defects were included as were those with ligamentous deficiencies provided they were addressed before or at the time of ACI grafting. Patients with isolated trochlea or patella defects were excluded as were those presenting with ongoing progressive inflammatory arthritis or varus-valgus abnormalities that required surgical correction ($<5^\circ$ tibiofemoral anatomic angle)²¹. None of the patients had ongoing concurrent orthopaedic conditions or sensorimotor impairments that would affect their ability to participate in the study, as determined by their orthopaedic specialist. Patients were referred directly to the study from

participating orthopaedic specialists who were aware of the inclusion/exclusion criteria, while no patients declined to participate in the study. The mean age of patients was 38.6 years, the average height was 175.1 cm, and body mass index was 81.8 kg/m². Ethical approval was obtained from the associated institutions and written informed consent from the participants was obtained before the onset of the study. A priori power calculation indicated a total sample size of 26 would reveal differences at the 1.7% significance level with a power of 0.8, using a moderate effect size of 0.6.

As part of a larger clinical trial being undertaken, patients were randomly assigned (block randomization, gender, and age younger or older than 40 years) to either “traditional” or “accelerated” load-bearing rehabilitation pathways. The “traditional” pathway consisted of a 5-week period of WB at 20% (toe-touch) BW, followed by a progressive rise in load bearing until full WB was attained at 11-weeks post-surgery. The “accelerated” load bearing gradient removed the initial 5-week toe-touch phase, whereby load bearing was progressively increased immediately with full WB attained at approximately 8-weeks post-surgery (Table 1). Only the accelerated group was subjected to a 40% BW WB stage (Table 1) and, for this reason, only 22 patients (the number of patients randomly assigned to the accelerated group) out of the total group of 48 underwent this WB condition (Table 2). Assessment at 20% and 60% BW WB levels were still undertaken in both groups at the same point in the postoperative timeline (Table 1), whereas the “accelerated” patient group underwent the 80% BW WB level two weeks earlier than the “traditional” group (Table 1). Furthermore, as a result of the late introduction of the static WB assessment, only 18 patients completed static replication trials at 20% BW (Table 2). Finally, although 48 patients participated in this study, the number who participated in both initial static and dynamic replication and 7-day retention trials differed among the 20%, 40%,

60%, and 80% BW WB levels (Table 2). This was the result of either the research design or factors beyond our control, including illness and missed sessions.

TABLE 1. The Load Bearing Protocols for both the Accelerated and Traditional Patient Groups. Patients were Assessed Immediately Following Instruction and Practice (A) and One Week After (B) Instruction

Traditional Group											
Weeks Post-surgery	2	3	4	5	6	7	8	9	10	11	12
Weight bearing (%BW)	20%				60%	60%	70%	80%	90%	100%	
Test Point #	20%A	20%B	N/A		60%A	60%B	N/A	80%A	80%B	N/A	
Crutches	2				1	1	1	1	1	1	0
Brace	Y				Y	Y	Y	Y	Y	Y	N
Accelerated Group											
Weeks Post-surgery	2	3	4	5	6	7	8	9	10	11	12
Weight bearing (%BW)	20%	30%	40%	50%	60%	80%	100%				
Test Point #	20%A	20%B	40%A	40%B	60%A	60B/80A	80%B	N/A			
Crutches	2	2	2	2	1	1	1	0			
Brace	Y	Y	Y	Y	Y	Y	Y	N			

BW = body weight

TABLE 2. Summary of Expected and Actual Weightbearing for Static, Initial Dynamic Replication and 7-day Retention Conditions Throughout 20%, 40%, 60%, and 80% Weightbearing Levels

Variable	Static Replication				Dynamic Replication				Dynamic Retention (7-day)			
Number of patients	18	22	43	40	41	22	43	40	41	22	43	40
Gender (M/W)	12/6	15/7	29/14	25/15	27/13	15/7	29/14	25/15	27/13	15/7	29/14	25/15
Age (years)	38.3	34.3	37.3	38.6	38.9	34.3	37.3	38.6	38.9	34.3	37.3	38.6
Body mass (kg)	88.6	77.1	82.2	82.2	82.7	77.1	82.2	82.2	82.7	77.1	82.2	82.2
VAS frequency (0-10)	2.5	2.5	2.6	2.5	2.5	2.5	2.6	2.5	2.5	2.5	2.5	2.7
VAS severity (0-10)	2.8	2.5	2.5	2.4	2.8	2.5	2.5	2.4	2.7	2.6	2.5	2.8
Expected WB (%BW)	20	40	60	80	20	40	60	80	20	40	60	80
Mean WB (%BW)	32.9	45.4	67.2	79.6	35.8	48.3	71.9	78.8	26.6	44.2	69.9	80.2
Difference (%BW)	+12.9	+5.4	+7.2	-0.4	+15.8	+8.3	+11.9	-1.2	+6.6	+4.2	+9.9	+0.2
Minimum (%BW)	8.2	11.7	45.9	68.3	8.4	15.3	53.9	61.4	2.8	18	52.5	67.3
Maximum (%BW)	54.9	81.1	94.4	90.2	71.1	66.6	93.8	94.3	59.7	89.6	93.3	95.6

M = men; W = women; VAS = visual analog scale; WB = weightbearing; BW = body weight

The bathroom scale method was used to train patients to follow the progressive WB program.

This method involved patients placing their affected leg on the scales (Electronic Tanita Wedderburn Scales, accuracy 0.1 kg; Tanita Corporation, Tokyo, Japan) with the unaffected leg

next to the scales on a platform at the same height (Fig 1). The patient performed three sets of 10 repetitions ramping up to the nominated weight using the electronic scales as a visual guide.

After this static loading practice, the patient walked for approximately 40 m at the nominated

PWB level and then returned to the scales to perform a final set of 10 static trials. All PWB

practice and assessment was undertaken in bare feet to ensure standardization across all patients.

At each postoperative stage, the patient was made aware of the PWB increment and any changes

with regard to the number of recommended walking aids. Patients wore a knee brace throughout

all WB conditions and used two forearm walking aids at the 20% and 40% BW WB stages and

one walking aid for the 60% and 80% BW WB stages as per the rehabilitation protocols. The

PWB increment was calculated based on the current weight of the patient.

Fig 1.

Immediately after instruction and practice, patients were assessed on their ability to replicate the PWB force on the foot of the affected leg within 5% of BW in a static standing position and while walking. The 5% BW level was an arbitrary value chosen due to the large variation in WB replication accuracy^{8,9,10,12,13,14} reported using scales in the available literature, while the majority of available research using scales reports accuracy outside 5% of BW.^{8,9,12,13,14}

Assessment was performed using a unidirectional force plate (sampling rate, 500 Hz) embedded in the center of a 5-m walkway to obtain the peak vertical GRF loads. The vertical load recorded

for each trial was the highest peak throughout the vertical GRF curve regardless of whether it occurred at heel strike or push off.

Patients were initially assessed on their ability to replicate the PWB level (20%, 40%, 60%, or 80% BW) in a static position. Patients were positioned with the affected leg over the force plate and the unaffected leg next to the force plate on the measuring platform (similar to that experienced during practice). The patient was asked to load their affected leg up to the nominated PWB level. A minimum of five practice trials in the static position were performed initially followed by five data collection trials with an average (\pm standard deviation) of the peak vertical loads recorded.

After these static trials, the patients were assessed on their ability to dynamically replicate the PWB level during level walking. Patients were asked to ignore the force plate and to walk as they would normally given their current stage of rehabilitation. The starting point for the patient was adjusted so they made contact with the center of the force plate without “targeting” and altering their walking gait. Once this had been achieved, the patient was permitted an additional two practice attempts for further familiarization that were followed immediately by the data collection trials. The number of trials for each subject was not standardized; three adequate trials were required.²² Therefore, repeated efforts were often needed for the patient to strike the center of the force plate with their affected leg on three occasions without making a conscious attempt to do so. A visual analog scale was administered to assess knee pain at the time of each assessment, whereby patients rated the frequency and severity of knee pain on a scale of 0-10

TABLE 2. Summary of Expected and Actual Weightbearing for Static, Initial Dynamic Replication and 7-day Retention Conditions Throughout 20%, 40%, 60%, and 80% Weightbearing Levels

Variable	Static Replication				Dynamic Replication				Dynamic Retention (7-day)			
Number of patients	18	22	43	40	41	22	43	40	41	22	43	40
Gender (M/W)	12/6	15/7	29/14	25/15	27/13	15/7	29/14	25/15	27/13	15/7	29/14	25/15
Age (years)	38.3	34.3	37.3	38.6	38.9	34.3	37.3	38.6	38.9	34.3	37.3	38.6
Body mass (kg)	88.6	77.1	82.2	82.2	82.7	77.1	82.2	82.2	82.7	77.1	82.2	82.2
VAS frequency (0-10)	2.5	2.5	2.6	2.5	2.5	2.5	2.6	2.5	2.5	2.5	2.5	2.7
VAS severity (0-10)	2.8	2.5	2.5	2.4	2.8	2.5	2.5	2.4	2.7	2.6	2.5	2.8
Expected WB (%BW)	20	40	60	80	20	40	60	80	20	40	60	80
Mean WB (%BW)	32.9	45.4	67.2	79.6	35.8	48.3	71.9	78.8	26.6	44.2	69.9	80.2
Difference (%BW)	+12.9	+5.4	+7.2	-0.4	+15.8	+8.3	+11.9	-1.2	+6.6	+4.2	+9.9	+0.2
Minimum (%BW)	8.2	11.7	45.9	68.3	8.4	15.3	53.9	61.4	2.8	18	52.5	67.3
Maximum (%BW)	54.9	81.1	94.4	90.2	71.1	66.6	93.8	94.3	59.7	89.6	93.3	95.6

M = men; W = women; VAS = visual analog scale; WB = weightbearing; BW = body weight

Immediately after the last dynamic gait trial, postresponse feedback on all static and dynamic replication trials for that session was provided to patients that included the maximum weight produced for each trial undertaken and how far the patient was over or under the designated WB level. This protocol for dynamic replication was repeated 7 days later in a dynamic WB retention test.

GRF data were collected through a custom-written Labview acquisition package (Labview 7.1; National Instruments Corp, Austin, TX) and processed within Microsoft Excel (Microsoft, Redmond, WA). The GRF data were first filtered using a low-pass Butterworth filter with a 2.5-Hz cutoff frequency, which was selected using residual analysis and visual inspection.²³ The GRF data were then normalized to 51 data points extending over the stance phase of the gait cycle. The level of WB exerted by patients in both initial replication (static and dynamic) and

followup retention trials (dynamic) were then converted and expressed as a percentage of patient BW (%BW) allowing comparison of actual and prescribed PWB levels.

A series of independent sample t-tests was initially used to compare expected WB with actual WB ability immediately after instruction in both static and dynamic conditions, and again dynamically 7-days later, throughout the selected target levels. Paired sample t-tests were used to analyze differences in dynamic WB ability immediately after instruction and 7-days later in the dynamic retention test. To adjust for these multiple comparisons, a Bonferroni correction was not used because this method is conservative, so statistical significance was determined at $p < 0.017$ (ie, $0.05 \div 3$).²⁴ Furthermore, linear regression was employed to investigate the strength of the relationship between static and dynamic WB replication error across the various WB conditions, whilst a Pearson correlation was used to assess the association between the two. The strength of Pearson correlations were defined as high, moderately high, moderate, low or no relationship.²⁵ Analysis was performed using SPSS software (version 11.5; SPSS Inc, Chicago, IL).

Results

Despite differing patient numbers between the three WB conditions (static, immediate dynamic and 7-day dynamic retention), and across all WB levels, the average age and ratio of males to females was similar between all groups (Table 2). There was no difference in the frequency and severity of reported knee pain from immediate to 7-day retention testing or throughout the four different WB conditions (Table 2).

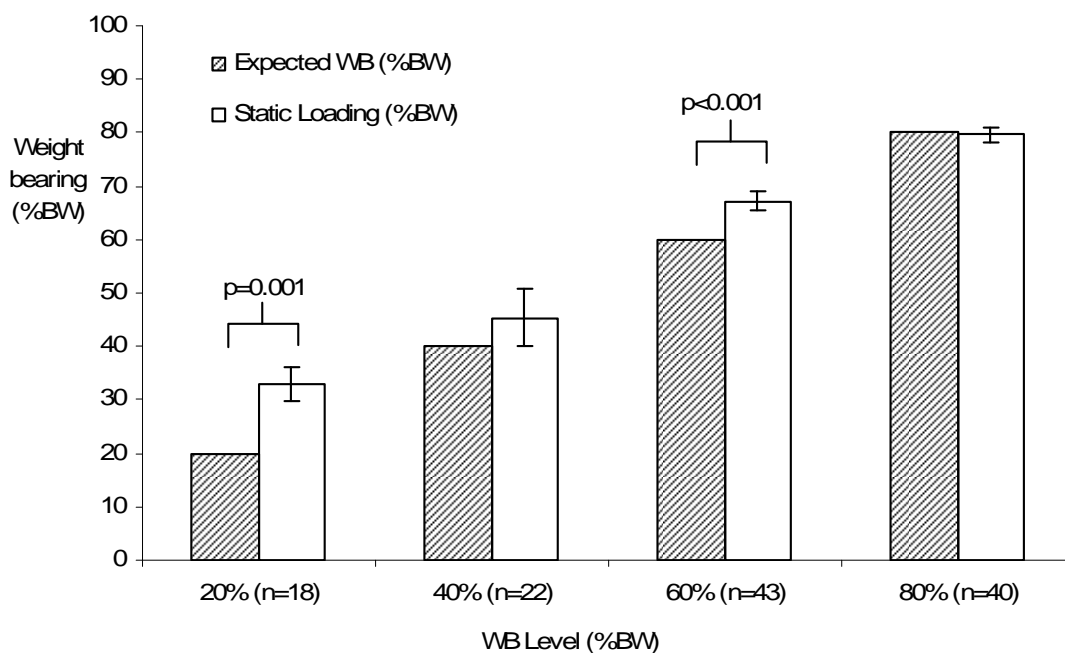
The 18 patients who completed initial static WB trials for the 20% BW WB level applied 12.9% BW more than the expected target, while the 22 patients who completed static WB replication trials for the 40% BW WB level applied 5.4% BW more than expected (Table 2) (Fig 2). The 43 patients completing static replication trials for the 60% BW WB level also applied 7.2% more than the expected target (Table 2) (Fig 2), while the 40 patients who completed initial static replication trials for the 80% BW WB level applied 0.4% less than expected (Table 2) (Fig 2). At least 58% of patients in each of the four WB conditions failed to maintain initial static WB within the 5% BW level, while no patient was within the 5% BW level for the 20% BW WB condition (Table 3). At least 51% of patients in the 20%, 40%, and 60% BW WB trials failed to maintain static WB within 10% of BW (Table 3).

TABLE 3. The Percentage of Patients Within the $\pm 5\%$ and $\pm 10\%$ BW Limits for Static, Initial Dynamic Replication and 7-day Retention Conditions Across the 20%, 40%, 60%, and 80% Weightbearing Levels

WB replication task	20% WB		40% WB		60% WB		80% WB	
	Within $\pm 5\%$ BW	Within $\pm 10\%$ BW	Within $\pm 5\%$ BW	Within $\pm 10\%$ BW	Within $\pm 5\%$ BW	Within $\pm 10\%$ BW	Within $\pm 5\%$ BW	Within $\pm 10\%$ BW
Static replication	0%	28%	23%	36%	30%	49%	42%	83%
Dynamic replication	22%	32%	32%	36%	26%	42%	46%	60%
Dynamic retention (7-day)	29%	66%	38%	62%	29%	53%	61%	89%

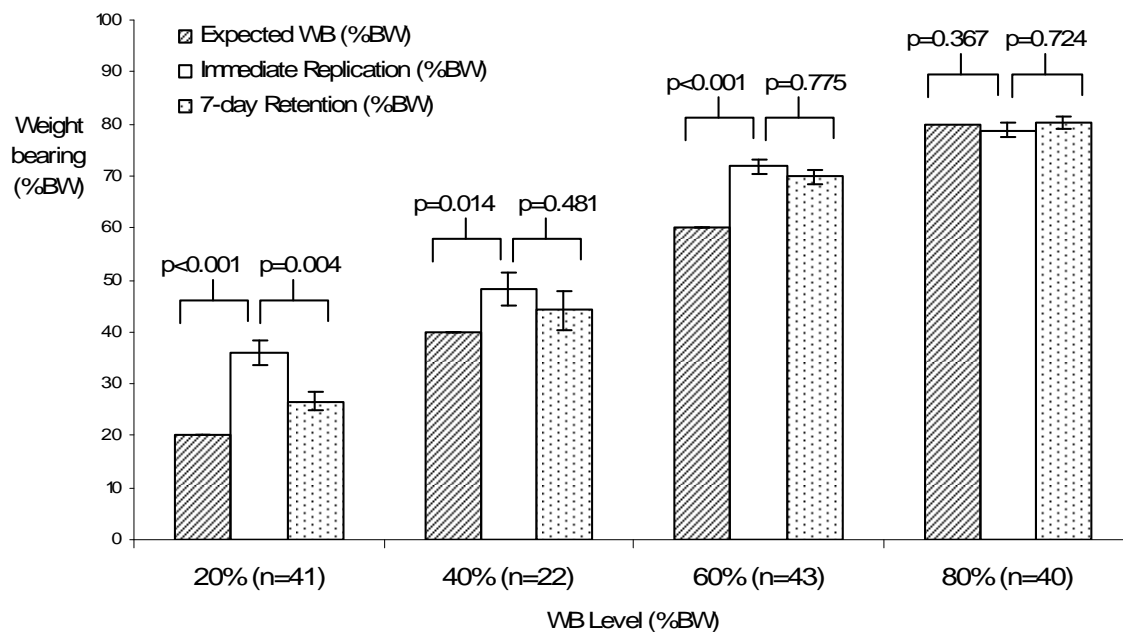
BW = body weight; WB = weightbearing

Fig. 2



The 41 patients who completed initial dynamic WB trials for the 20% BW WB level applied 15.8% BW more than the expected target during gait, while the 22 patients who completed initial dynamic WB trials for the 40% BW WB level applied 8.3% BW more than expected (Table 2) (Fig 3). The 43 patients completing initial dynamic trials for the 60% BW WB level also applied 11.9% BW more than the expected target, while the 40 patients who completed initial dynamic replication trials for the 80% BW WB level applied 1.2% BW less than the expected target (Table 2) (Fig 3). At least 54% of patients in each of the four WB conditions failed to maintain initial dynamic WB within the 5% BW level (Table 3), while at least 58% of patients failed to maintain dynamic WB within 10% of BW for the 20%, 40%, and 60% BW WB trials (Table 3).

Fig 3.

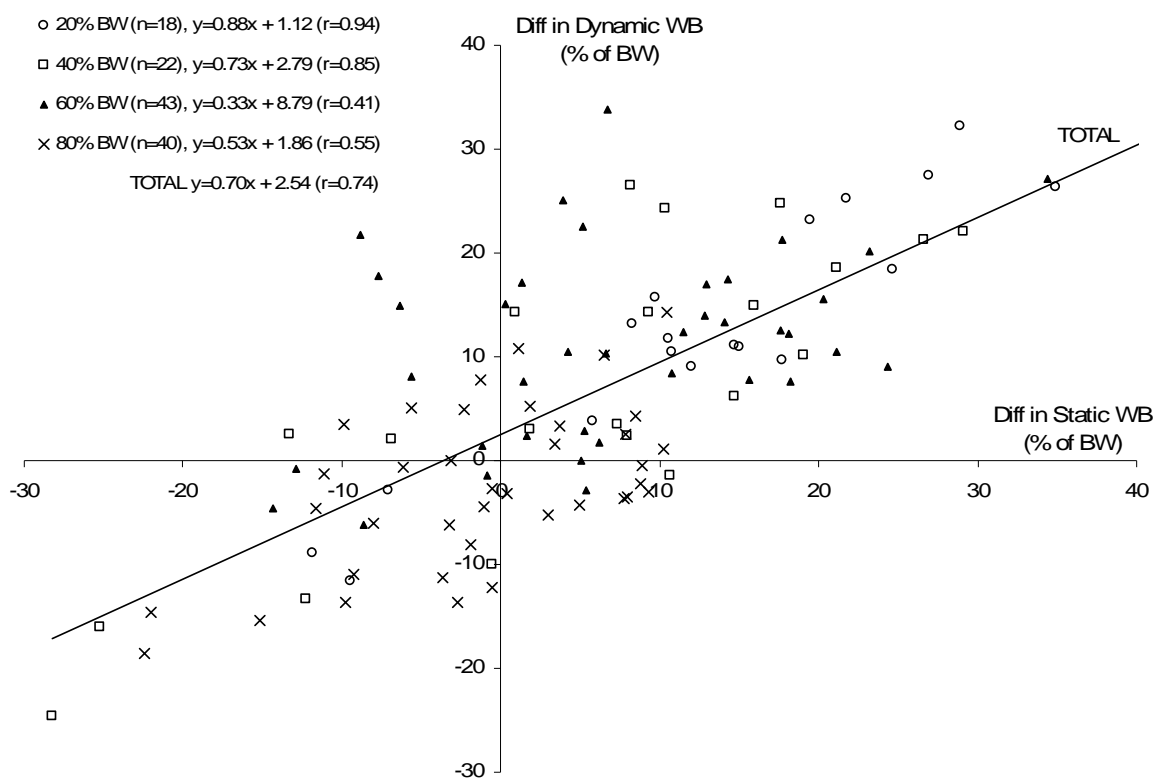


For the 7-day dynamic retention trials, patients exerted 6.6%, 4.2%, 9.9% and 0.2% BW more than expected for the 20%, 40%, 60% and 80% BW WB trials, respectively (Table 2) (Fig 3). At least 62% of patients within each of the 20%, 40%, and 60% BW WB conditions failed to maintain 7-day dynamic retention within 5% of BW, while at least 53% of patients within all four WB conditions were within 10% BW for the 7-day retention trials (Table 3).

There was a significant improvement ($p = 0.004$) in WB accuracy from initial to 7-day dynamic WB replication within the 20% BW WB trials, but we observed no differences across the 40%, 60%, and 80% BW WB conditions (Fig 3). Patient numbers in the 40% BW WB level were below our priori patient sample calculation of 26 (Table 2).

Pearson correlations between static and dynamic WB replication error revealed a moderately high relationship between replication errors in both static and dynamic conditions across all WB conditions ($y = 0.70x + 2.54$, $r = 0.74$), whereas a high relationship was observed within the 20% ($y = 0.88x + 1.12$, $r = 0.94$) and 40% ($y = 0.73x + 2.79$, $r = 0.85$) BW WB levels alone (Fig 4).

Fig 4.



Discussion

A specific PWB program plays an essential role in providing both a protective and progressive stimulus to developing chondrocytes after ACI.²⁶ It is therefore important for patients to closely

replicate these graduated WB programs so under- or overstimulation of the graft at any stage throughout the postoperative timeline does not occur, possibly hampering the attainment of best-quality tissue repair. Instruction and practice using a set of scales is a common and practical method of imposing these WB restrictions during walking.^{5,8,11} However, differing success has been reported with the use of this technique,^{8,9,10,12,13,14,17} the majority of the available literature revealing replication of WB using scales outside 5% of BW.^{8,9,12,13,14} Although this method has undergone trials in unaffected subjects^{8,9,10,11,12,13,17,18} and patients after other orthopaedic procedures,^{7,9,18} it has not been investigated in postoperative patients having undergone ACI in which replication of WB may be crucial to the protection, and development of repair tissue. Therefore, we sought to investigate whether patients undergoing ACI could replicate a series of nominated WB levels encountered throughout their postoperative WB rehabilitation program.

Although a graduated WB program is believed to provide protection and progressive stimulation to the developing chondrocytes after ACI, optimal protocols have yet to be established. For this reason, the result of patients' inability to replicate desired WB levels on the short- and long-term outcome of repair tissue after ACI is unknown. Our study did not address the biological outcome of repair tissue after under- or overloading of external WB throughout the postoperative program but rather the patient's ability to replicate these WB restrictions.

Furthermore, we acknowledge that more time spent practicing PWB may prove beneficial in accuracy of replication during gait. However, the level of instruction and practice performed in the current study indicates that which may be routinely provided, whereas anything more may not be practical in a clinical setting.

Our first hypothesis that patients were unable to replicate 20% (32.9% BW), 40% (45.4% BW), and 60% (67.2% BW) BW WB restrictions statically within 5% of BW immediately after practice and instruction using static loading was supported. Despite the overall mean for the static 80% BW WB condition being within 5% BW (79.6% BW), 58% of patients were still outside this limit, whereas 100% of patients who performed loading at the 20% level were outside the predicted 5% BW limit (Table 3). Accurate replication ability during the 20% BW WB stages following ACI are of particular importance, since they generally correspond with more crucial, earlier postoperative time points and, therefore, more potential for graft delamination. The inaccuracy reported is in contrast to Malviya et al¹⁰ who demonstrated good static replication of a 25% BW WB restriction; however, only healthy, unaffected subjects were used.

Similar to the static WB condition, patients were unable to replicate loads of 20% BW (35.8% BW) during walking immediately after instruction (Table 2) (Fig 3), with 78% of patients outside the 5% BW limit (Table 2). These findings were similar to those reported in the literature,^{9,14} whereby Dabke et al⁹ reported 21 of 23 patients, after a range of orthopaedic procedures, exerted a mean of 35.3% BW more than prescribed (20%-40% WB restriction) using the bathroom scale method. This inability to replicate low levels of WB has also been observed in patients following total hip arthroplasty⁷ and surgical intervention to address lower limb fractures.¹⁹ Patients failed to replicate WB levels of 40% (48.3% BW) and 60% (71.9% BW) BW during walking immediately after instruction (Fig 3). This finding is in contrast to Youdas et al¹² who demonstrated good reproducibility of 50% PWB during walking in unaffected subjects using axillary and forearm walking aids after training on bathroom scales,

however, only a small sample of healthy participants was used. In the current study, patients were accurate in replicating loads of 80% BW (78.8% BW) during gait possibly since 80% BW WB is close to full WB. Therefore, although WB accuracy during walking was within the 5% BW target cutoff for the 80% BW WB level, our second hypothesis was supported for the 20%, 40%, and 60% BW WB conditions.

Furthermore, patients failed to replicate WB levels of 20% (26.6% BW) and 60% (69.9% BW) BW during 7-day dynamic retention trials (Fig 3), which is again in contrast to previous findings.¹² In the current study, patients were accurate in replicating loads of 40% (44.2% BW) and 80% BW (80.2% BW) during walking in the 7-day retention condition. Therefore, although WB accuracy during walking was within the 5% BW target cutoff for the 40% and 80% BW WB levels, our third hypothesis was supported for the 20% and 60% BW WB conditions.

Again, since the 20% BW WB condition corresponds with earlier and, therefore, more crucial postoperative time points accurate replication ability should be of particular importance. It is yet unknown how overloading of the graft in the early stages (as was the case in the study) may affect long term graft development.

Static WB practice using the bathroom scale method does not replicate the situation experienced during dynamic WB gait.⁸ Dynamic gait introduces outside influences in addition to BW such as acceleration of the body and limbs. In addition, to simulate a walking surface, the measuring device must lie in the same plane as the walking surface. If not, the relative length of limbs and ambulatory aids changes.⁸ An attempt was made to overcome this issue by allowing the patient to support their nonaffected leg on a platform the same height as the scales (Fig 1). Furthermore,

it must be acknowledged that the number of walking aids employed varied depending on the level of WB restriction imposed as per the patients' rehabilitation program (ie, two crutches for 20% and 40% BW WB, and one crutch for 60% and 80% BW WB). Although the purpose of this study was to investigate WB ability given the designated WB protocols, rather than the effect that 'type' and 'number' of assistive devices has on WB ability, this may still influence the ability to weightbear between these different WB conditions.

Although age has been shown to affect WB accuracy,¹⁹ the average age, and ratio of males to females was similar between the different WB conditions, and across all WB levels. Therefore, the influence these factors had on WB accuracy differences between groups should have been negligible. Other factors that are often present in the postoperative patient having undergone ACI such as pain,⁹ reduced power,²⁰ an altered mental state and fragility after the operative procedure may also affect PWB ability. Therefore, the influence each of these factors will have on the ability to follow WB restrictions will depend on the individual patient's physical and emotional strength, analgesic use, and tolerance to pain as well as the progression of pathologic parameters (ie, pain and joint effusion) throughout the early postoperative timeline. Knee joint effusion was not assessed in this study and may have contributed to differences in WB ability, particularly in the early post-operative stages. However, knee pain before each trial was recorded and was constant from immediate replication to 7-day retention assessments and across all WB conditions (Table 2). Therefore, the influence knee pain had on the observed differences in WB accuracy across WB conditions should have been negligible.

There was no improvement in WB accuracy during walking between immediate and 7-day retention replication for the 40%, 60%, and 80% BW WB conditions, which supported our fourth hypothesis. However, patient numbers in the 40% BW WB level were below our priori patient sample calculation of 26, indicating the sample may not have been substantial in detecting significant changes. We observed an improvement for the 20% BW WB trials (Fig 3). Previous studies suggest the effect of training in PWB may be limited whereby learning diminishes rapidly 1 to 2 days posttraining;^{13,17} however, some form of postresponse feedback may improve long-term learning.¹¹ The improvement in WB accuracy observed across the 7-day period for the 20% BW WB condition suggests a quick and simple analysis of patient WB (feedback) after practice trials may be beneficial in improving WB ability over 7 days, at least at low WB loads around 20% BW.

A moderately high relationship was observed between static and dynamic replication error across all WB conditions, whereas this association was high within 20% and 40% BW WB conditions (Fig 4), supporting our fifth hypothesis. This relationship observed between static and dynamic replication error suggests training should target those who have large static WB replication errors, particularly at low WB loads. Furthermore, the ability of patients to replicate the WB levels revealed low accuracy in replicating the lowest level target (20% BW) and better performance at the highest load (80% BW). Although these findings are both similar^{7,9,18,19} and in contrast^{10,12} to those reported previously, it does suggest more emphasis should be placed on training the lower PWB levels.

Conclusions

Patients undergoing ACI were unable to replicate static and dynamic WB restrictions of 20%, 40%, and 60% BW within 5% of BW after practice and instruction using the bathroom scale technique. These results are both comparable and in contrast to those reported in the literature; however, research has focused on unaffected subjects^{8,9,10,11,12,13,17,18} and patients with other orthopaedic procedures.^{7,9,19} Patients were accurate in replication of the high WB loads (ie, 80% BW) whilst inaccurate during the low WB loads (ie, 20% BW). This early stage corresponds with a more crucial point in the post-operative timeline, and for this reason more emphasis should be placed on training these lower WB levels. Furthermore, patients who demonstrated greater static replication error displayed greater replication error during gait and, therefore, should the rehabilitation facility not have easy access to a dynamic force platform, the patient may marginally benefit from extra time spent practicing static PWB on a set of bathroom scales. These findings can be used to improve WB instruction protocols and patient accuracy throughout rehabilitation after other lower limb orthopaedic procedures when WB restrictions should be followed. Furthermore, future research should be directed at how WB inaccuracy (and in particular overloading), especially in the crucial early stages following ACI, as well as how differing post-operative WB protocols may affect long-term graft development.

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References

1. Brittberg M, Lindahl A, Nilsson A, Ohlsson C, Isaksson O, Peterson L. Treatment of deep cartilage defects in the knee with autologous chondrocyte transplantation. *N Engl J Med* 1994;331:889-95.
2. Gillogly SD, Voight M, Blackburn T. Treatment of articular cartilage defects of the knee with autologous chondrocyte implantation. *J Orthop Sports Phys Ther* 1998;28:241-51.
3. Peterson L, Minas T, Brittberg M, Nilsson A, Sjogren-Jansson E, Lindahl A. Two- to 9-year outcome after autologous chondrocyte transplantation of the knee. *Clin Orthop Relat Res* 2000;374:212-34.
4. Ronga M, Grassi FA, Bulgheroni P. Arthroscopic autologous chondrocyte implantation for the treatment of a chondral defect in the tibial plateau of the knee. *Arthroscopy* 2004;20:79-84.
5. Hambly K, Bobic V, Wondrasch B, Van Assche D, Marlovits S. Autologous chondrocyte implantation postoperative care and rehabilitation: science and practice. *Am J Sports Med* 2006;34:1-19.
6. Robertson WB, Gilbey H, Ackland T, editors. *Standard Practice Exercise Rehabilitation Protocols for Matrix Induced Autologous Chondrocyte Implantation Femoral Condyles*. Perth, Western Australia: Hollywood Functional Rehabilitation Clinic; 2004.
7. Hurkmans HL, Bussmann JB, Selles RW, Benda E, Stam HJ, Verhaar JA. The difference between actual and prescribed weight bearing of total hip patients with a trochanteric osteotomy: long-term vertical force measurements inside and outside the hospital. *Arch Phys Med Rehabil* 2007;88:200-6.

8. Gray FB, Gray C, McClanahan JW. Assessing the accuracy of partial weight-bearing instruction. *Am J Orthop* 1998;27:558-60.
9. Dabke HV, Gupta SK, Holt CA, O'Callaghan P, Dent CM. How accurate is partial weightbearing? *Clin Orthop Relat Res* 2004;421:282-6.
10. Malviya A, Richards J, Jones RK, Udawadia A, Doyle J. Reproducibility of partial weight bearing. *Injury* 2005;36:556-9.
11. Winstein CJ, Pohl PS, Cardinale C, Green A, Scholtz L, Waters CS. Learning a partial-weight-bearing skill: effectiveness of two forms of feedback. *Phys Ther* 1996;76:985-93.
12. Youdas JW, Kotajarvi BJ, Padgett DJ, Kaufman KR. Partial weight-bearing gait using conventional assistive devices. *Arch Phys Med Rehabil* 2005;86:394-8.
13. Warren CG, Lehmann JF. Training procedures and biofeedback methods to achieve controlled partial weight bearing: an assessment. *Arch Phys Med Rehabil* 1975;56:449-55.
14. Li S, Armstrong CW, Cipriani D. Three-point crutch walking: variability in ground reaction force during weight bearing. *Arch Phys Med Rehabil* 2001;82:86-92.
15. Gapsis JJ, Grabois M, Borrell RM, Menken SA, Kelly M. Limb load monitor: evaluation of a sensory feedback device for controlled weight bearing. *Arch Phys Med Rehabil* 1982;63:38-41.
16. King PS, Gerhardt JJ, Pfeiffer EA, Usselman LB, Fowlks EW. System for controlling ambulation pressure (SCAP-3) in patients with disabilities of the lower extremity. *Am J Phys Med* 1972;51:9-15.
17. Tveit M, Karrholm J. Low effectiveness of prescribed partial weight bearing. Continuous recording of vertical loads using a new pressure-sensitive insole. *J Rehabil Med* 2001;33:42-6.

18. Krause D, Wunnemann M, Erlmann A, Holzchen T, Mull M, Olivier N, Jollenbeck T. Biodynamic feedback training to assure learning partial load bearing on forearm crutches. *Arch Phys Med Rehabil* 2007;88:901-6.
19. Vasarhelyi A, Baumert T, Fritsch C, Hopfenmuller W, Gradl G, Mittlmeier T. Partial weight bearing after surgery for fractures of the lower extremity - is it achievable? *Gait Posture* 2006;23:99-105.
20. Chow SP, Cheng CL, Hui PW, Pun WK, Ng C. Partial weight bearing after operations for hip fractures in elderly patients. *J R Coll Surg Edinb* 1992;37:261-2.
21. Robertson WB, Fick D, Wood DJ, Linklater JM, Zheng MH, Ackland TR. MRI and clinical evaluation of collagen-covered autologous chondrocyte implantation (CACI) at two years. *The Knee* 2007;14:117-27.
22. Hughes J, Clark P, Klenerman L. The importance of the toes in walking. *J Bone Joint Surg Br* 1990;72:245-51.
23. Winter D. *Biomechanics and Motor Control of Human Movement*. 2nd ed. New York: John Wiley; 1990.
24. Smith AJ, Lloyd DG, Wood DJ. Pre-surgery knee joint loading patterns during walking predict the presence and severity of anterior knee pain after total knee arthroplasty. *J Orthop Res* 2004;22:260-6.
25. Safrit M. *Introduction to Measurement in Physical Education and Exercise Science*. St Louis, Missouri: Times Mirror/Mosby College Publishing; 1986.
26. Willers C, Wood D, Zheng MH. A current review on the biology and treatment of articular cartilage defects (parts I & II). *J Musculoskel Res* 2003;7:157-81.

Legends

Fig 1. With this load-bearing practice condition, the patient learns a new partial weightbearing level on a set of scales to replicate that weight during walking.

Fig 2. Although static replication of weightbearing (WB) was only significantly greater ($p < 0.017$) than expected for the 20% and 60% body weight (BW) WB conditions, patients exerted more than 5% BW over the expected target for the 20%, 40% and 60% BW WB trials. Patients were within 5% BW for the 80% BW WB static condition.

Fig 3. Immediate dynamic replication of weightbearing (WB) was significantly greater ($p < 0.017$), and more than 5% BW over the expected target for 20%, 40% and 60% body weight (BW) WB trials, while dynamic replication was within 5% BW for the 80% BW WB condition. Dynamic replication of WB improved ($p < 0.017$) over a 7-day retest period for the 20% BW WB level only.

Fig 4. Pearson correlations showed patients who were poor at replicating WB restrictions statically were also poor at replication during gait, indicated by a moderately high relationship ($y = 0.70x + 2.54$, $r = 0.74$) between static and dynamic weightbearing (WB) replication error across all WB conditions (difference in expected and actual WB expressed as a percentage of body weight [BW]). A high relationship existed within the 20% ($y = 0.88x + 1.12$, $r = 0.94$) and 40% ($y = 0.73x + 2.79$, $r = 0.85$) BW WB levels.