
INTRODUCTION
Cyclic testing of flexor tendon repairs in vitro involves a relatively greater level complexity compared to static pull-to-failure testing. The clinical utility of ultimate repair strength under static conditions is limited. A well-constructed multi-strand repair is regarded as capable of handling early unresisted active mobilization. The ability of multi-strand repair techniques to resist gap formation with cyclic stress maybe a better indicator of in vivo performance. But accurate gap measurement during mechanical loading is not straightforward and several difficult approaches have been documented including the use of an extensimeter, fluoroscopy of intratendinous markers, a Hall-transducer, and continuous filming. A simple reproducible approach using basic equipment is desirable.

This study examined the relationship between gap and displacement during cyclic testing and the feasibility of interpolating gaps using displacement data and the gaps measured pre and post-cycling. A common 2-strand repair and 4-strand repair both with and without a peripheral suture were evaluated for this purpose. The ability to interpolate gaps at different cycles may improve our ability to make more effective comparisons across different cyclic testing studies.

MATERIALS AND METHODS
Sixteen sheep hind limb deep flexor tendons were randomized into four groups of n = 4 each. Linear mechanical testing was performed at room temperature using a MTS 858 Mini Bionix materials testing machine (MTS Systems. Eden Prairie, MN). Tendons were gripped in the same orientation between grooved pneumatic clamps with a 35mm gauge length. Intact tendons were preconditioned for 10 cycles at the testing loads before being transected at a standardized point and repaired. Groups 1 and 2 were repaired with a 2-strand Pennington modified Kessler repair and Groups 3 and 4 repaired with a 4-strand cross-locked cruciate (Adelaide) repair. A simple running 14 loop peripheral suture was added to groups 1 and 3. 4-0 Ticron was used for the core repairs. 6-0 Prolene was used for the peripheral repairs. 4-0 silicone coated braided polyester suture (Ticron; Tyco. Norwalk, CT) was used for all core repairs. 6-0 polypropylene monofilament suture (Prolene; Ethicon. Somerville, NJ) was used for all peripheral repairs.

Repaired tendon were cycled for 1000 cycles at 0.4Hz between 2-20N for the 2-strand repairs (mimicking passive rehabilitation loads), and between 3-30N for the 4-strand repairs (mimicking active rehabilitation loads). 2-strand repairs are not designed to tolerate active rehabilitation, and two pilots failed under 3-30N loading. Time (ms), load (N), cycle and displacement (mm) were continuously recorded. Cycling was paused intermittently and the displacement and maximum gap measured at 18 cycle points for each tendon: 0, 5, 10, 20, 50, 100, 150, 200, 250, 300, 350, 400, 450, 500, 600, 700, 800, and 1000 cycles.

Maximum gaps were measured with tendons held at trough loads (2N and 3N for passive and active groups, respectively). Measurements were made from high resolution digital images taken with a Canon EOS 1000D digital SLR camera with Canon EF 100mm macro lens (Canon Inc. Tokyo, Japan) fixed on a tripod. A digital caliper fixed at 10.0mm served as a calibration device in the digitized image. The gaps were calculated by comparing the relative number of pixels at the point of maximum gapping to that between caliper tips using Image J v1.41o (National Institute of Health).

MATLAB 7.8.0 R2009a (Mathworks. Natick, MA) was used for data analysis. Simple linear regression was used to evaluate the relationship between measured gaps and displacement. An equation for the interpolated gap versus displacement lines was generated using displacement and measured gap data at zero and 1000 cycles. Using the equation, the interpolated gaps were calculated for each corresponding gap that was measured. The absolute differences between measured and interpolated gaps were evaluated for each repair. Reliability analysis with the intraclass correlation coefficient was undertaken to determine the strength of association between interpolated gaps and measured gaps for each group. Data points used in deriving the gap interpolation function were excluded in the reliability analysis.

RESULTS
All repairs survived to 1000 cycles with the exception of one repair in group 2. There was a strong positively linear relationship between gap and displacement for each of the repair groups (Figure 1). R² was >0.90 for all repairs. There was an initial non-linear segment during the first 10 cycles noted particularly with some of the composite repairs. The correlation coefficient was higher when the interval between 10 and 1000 cycles was taken for these groups.

The maximum difference between measured and interpolated gap was 0.67mm using the first (cycle 0) and last (cycle 1000) data points for the interpolation function. The mean and maximum differences were significantly reduced when the third (cycle 10) and last data points were used (Figure 2). The maximum difference between measured and interpolated gaps between 10 and 1000 cycles was <0.25mm, with a mean difference <0.1mm for all groups. The ICC was >0.95 for all groups.

DISCUSSION
This study demonstrated a strong linear relationship between the displacement and maximum gap formation between 10 and 1000 cycles of loading. This relationship held true for a prevalent 2 and 4 strand repair technique both with and without a peripheral suture. We hypothesize that the non-linear segment in early cycling of composite repairs was predominantly related to an accommodation of different suture strands as load distribution equilibrated. Allowing 10 cycles of “conditioning” prior to undertaking further analysis improved the reliability of our method.

The interpolation of gap at any cycle between two extreme points simplifies the cycling protocol by avoiding interruptions to testing or the use of complex setups required for continuous monitoring of gap. It allows more flexible data analysis and a facility to “retrieve” data, helping to improve the comparison of dynamic gapping with existing cyclic testing studies as well as future studies. The error between measured gaps and gaps interpolated using this method are small and of negligible clinical significance. Testing should be paused at 10 cycles to measure gap at this point, but does not need to be further interrupted until 1000 cycles. Alternative testing protocols and repair techniques should be validated prior to applying this method.