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# A Novel Quantitative Assessment of Bone Tendon Junction Healing in Patients after ACL Reconstruction by High Resolution Peripheral Computer Tomography: the Development of a Deep Learning System

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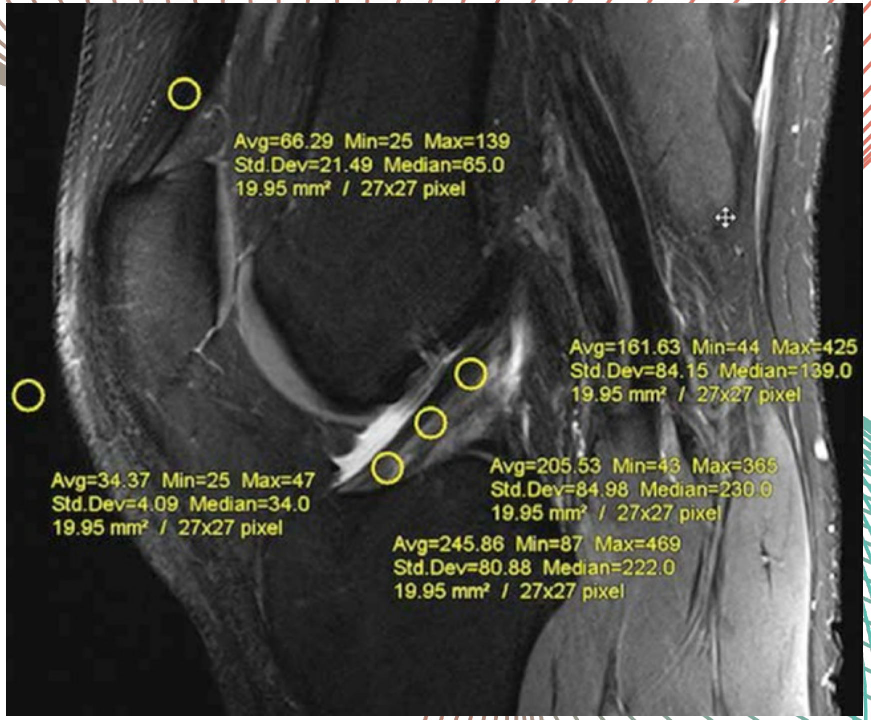
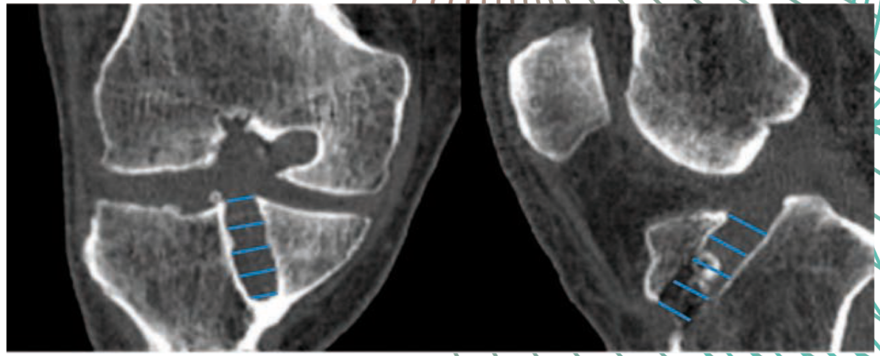
# Background

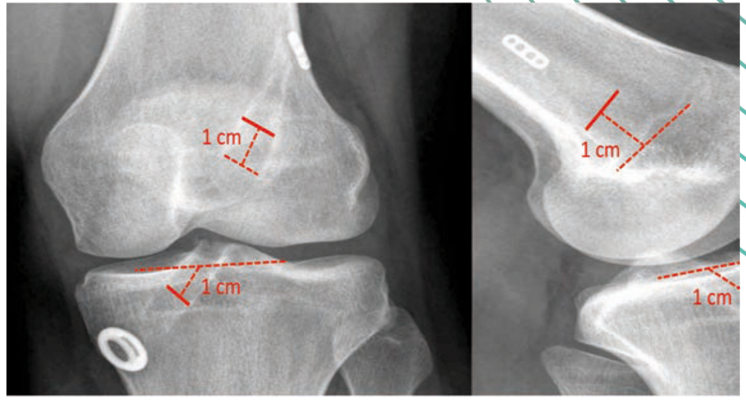
- Unsatisfactory graft healing after ACLR is one of the causes of graft failure (1,2)
- Furthermore, limited studies have correlated bone tendon healing status with clinical outcomes
- Knee stability and patient reported outcome measures (PROMs) are only indirect measures of graft healing
- While histologic analysis during second look arthroscopy is the gold standard for graft healing, its invasive nature makes it impractical. Therefore, assessment of bone tendon healing mainly rely on imaging modalities
- Previous studies have measured tunnel size (3), while others have used MRI signal to noise quotient (SNQ) as a function of graft maturity (4)




Hofbauer KSSTA 2019



De Beus Muscle, ligaments and Tendons J 2017

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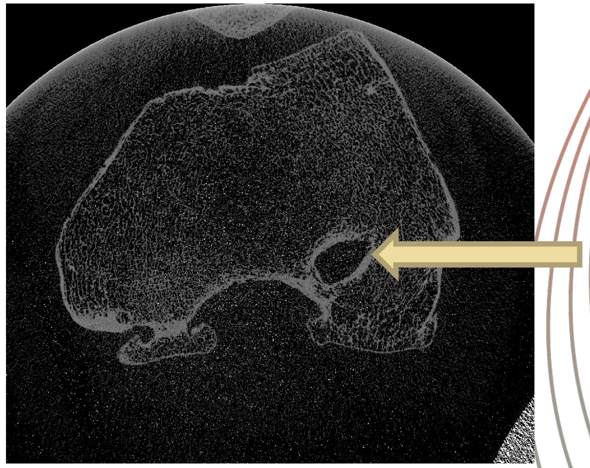
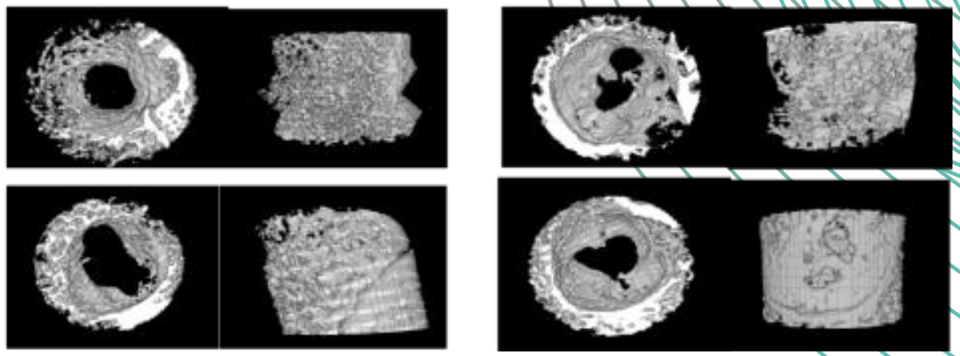
# Background

- Xtreme-CT, is a high resolution peripheral quantitative CT (HR-pQCT) that is highly sensitive in evaluating bone mineral density and microarchitecture (5)
- Previous animal studies have reported a positive correlation between the tendon graft-bone interface strength and the degree of bony mineralization, and tissue maturation at the interface (6)
- The increase in bone density at the tendon graft-bone interface, or the “bone shell” on the HR-pQCT, may reflect the degree of osseous ingrowth and the healing status of the bone tendon junction



Bone shell



# Objective

- To devise a novel quantitative assessment of peri-tunnel bone shell size
- To determine the association of peri-tunnel bone shell size to functional recovery after ACLR

## Hypothesis:

- The bone shell formation at graft-tunnel interface can represent the extent of bony changes, which reflects the extent of osteointegration of graft
- The peri-tunnel bone shell size is positively correlated with functional recovery after ACLR

# Methods

- 24 patients with primary unilateral ACLR performed recruited
- Postoperative HR-pQCT (Xtreme CT) was performed in all patients
- Axial cuts of the femoral and tibial tunnels were extracted for image analysis
- The bone shell was traced and the area was then calculated
- IKDC scores were charted
- Quadriceps muscle bulk assessment with ultrasonography (Aixplorer® ultrasound scanner) was performed in all patients

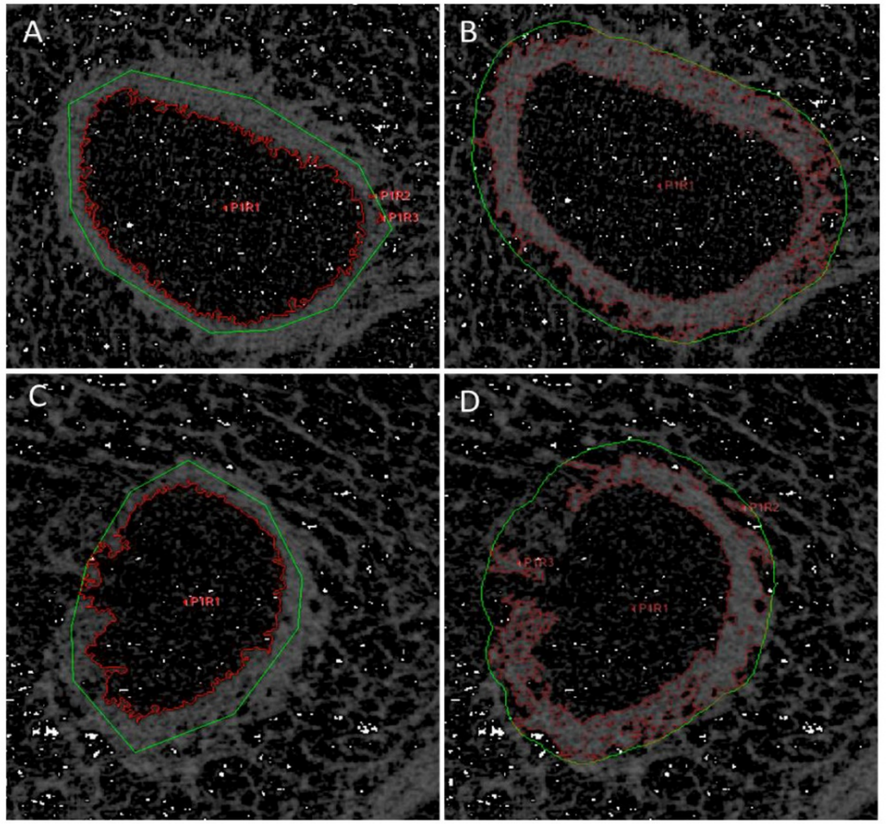
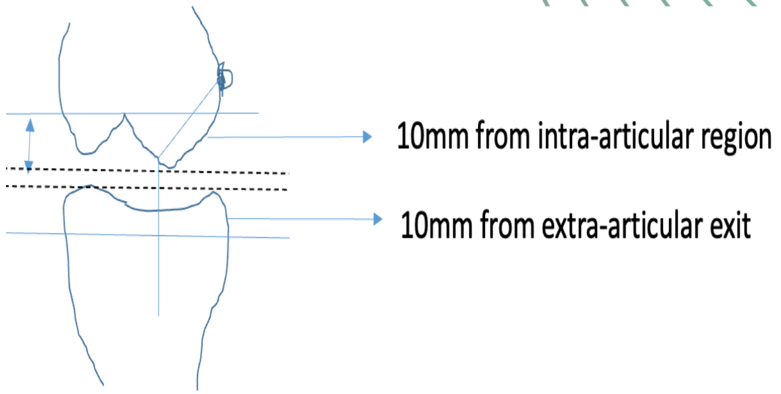



**Figure 1:** CT images of femoral (**A, B**) and tibial (**C, D**) tunnels are extracted for image analysis. The region of interest (ROI) for tunnel area is drawn by tracing the bone shell (**green line in A, C**), then a pre-set thresholding values will be applied to select the dark region inside the bone shell as tunnel area (**red line in A, C**). The contour of the tunnel area will be dilated for 30 pixels to obtain the ROI for bone shell measurement (**green line in B, D**), then another pre-set thresholding values will be applied to select the bone features as bone shell area (**red line in B, D**).

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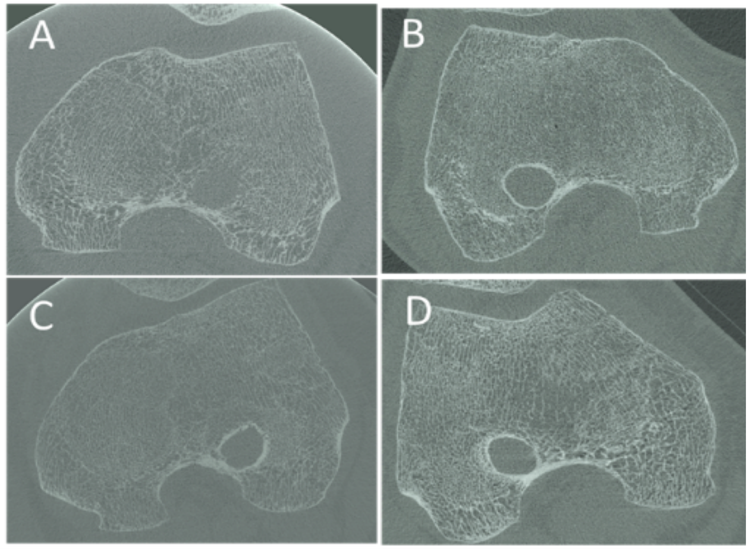
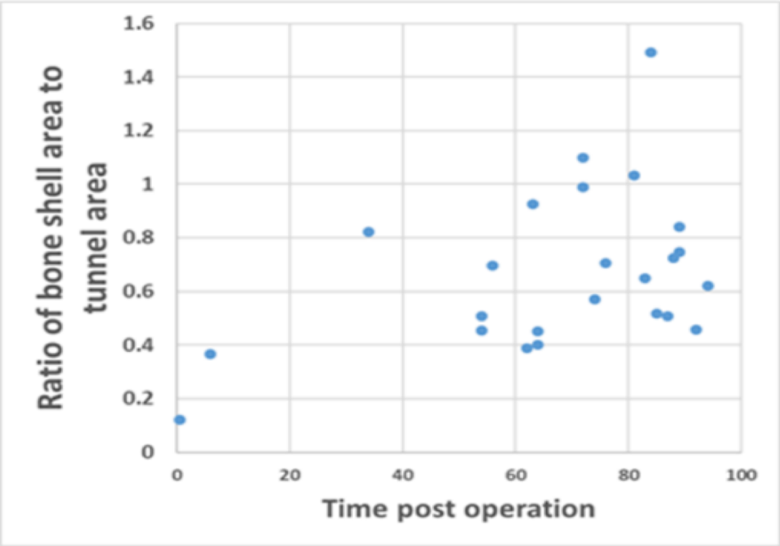
# Results

## Baseline demographics

| Parameters | Mean +/- Standard Deviation |
|---|---|
| Number of Cases (n=24) | |
| Age (years) | 33.3 ± 5.8 (Range: 24-42) |
| Gender | 17 Male; 7 Females |
| Height (cm) | 171.9 ± 10.0 |
| Weight (kg) | 78.5 ± 12.7 |
| BMI | 25.9 ± 4.1 |
| Time post-op | 2 weeks-94months |




- Bone shell formation occur as early as 0.5 months post ACLR
- This continued to remodel until 9 years post ACLR

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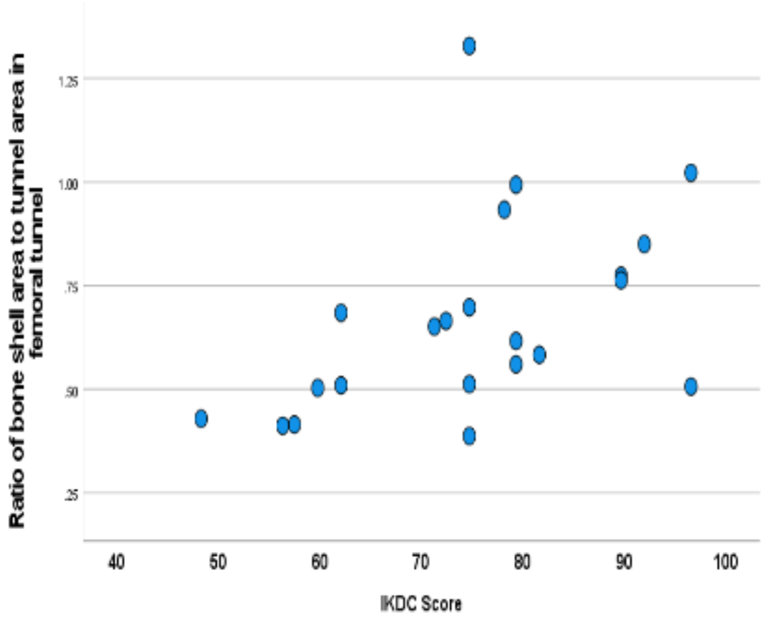
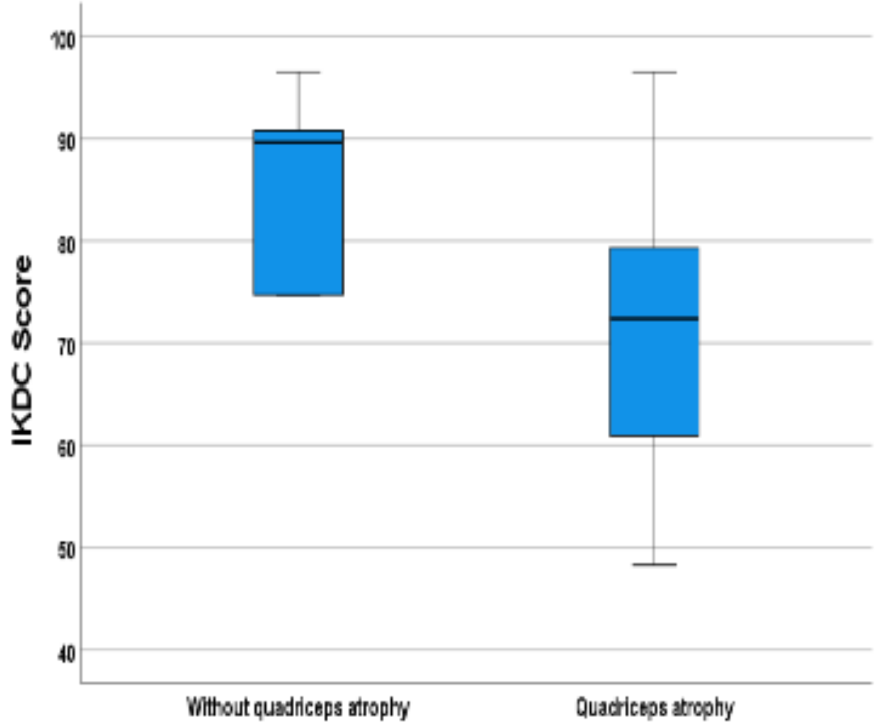
# Results

- Bone shell formation in femoral tunnel (standardized β= 0.440, p=0.022) were significantly associated with IKDC scores (adjusted R square= 0.376).




- Quadricep atrophy (standardized β=-0.400, p=0.036) significantly associated with IKDC scores



# Discussion

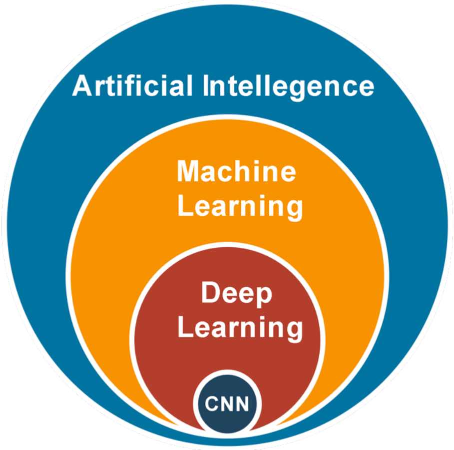
- First study to use high-resolution CT to quantitatively assess peri-tunnel bone formation
- The thickness of bone shell formation positively correlated with IKDC scores
- Clinical implications: potentially can be used for assessment of bone tendon junction healing
  - Customized rehabilitation program according to healing
  - Contribute to evaluation for safe return-to-play after ACLR.
  - Help evaluate biological modulation to promote graft healing in ACLR

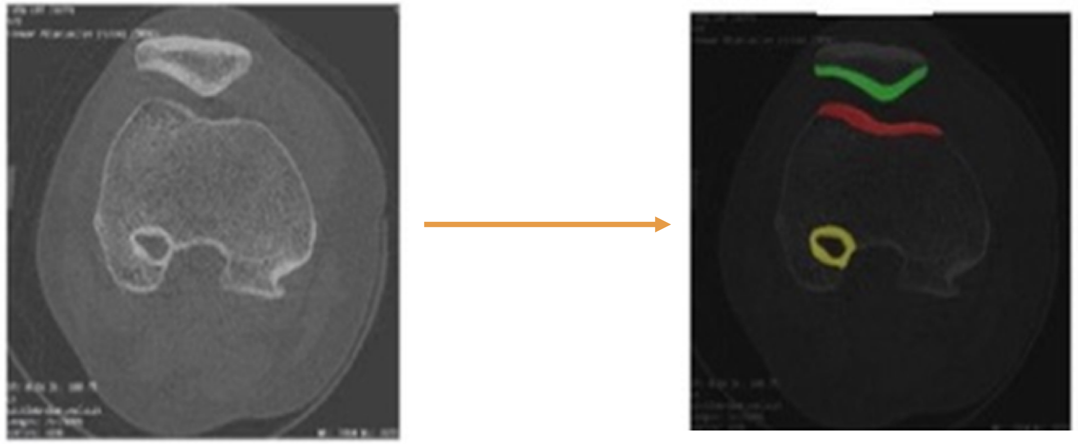
# Discussion

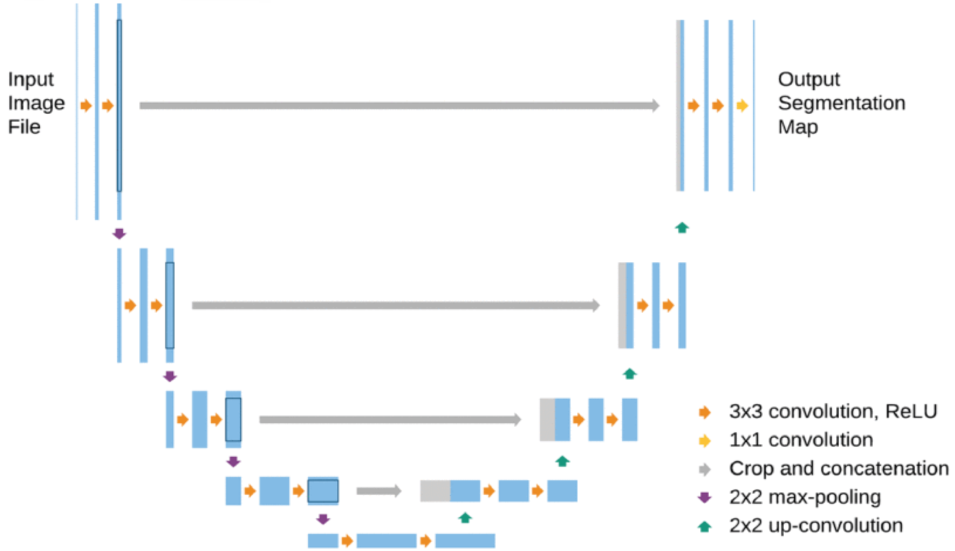
- One of the limitations of this technique is the laborious process of manual image analysis
- This has led to the development of machine learning to facilitate the efficiency of this process
- We have an ongoing study employing U-Net as a machine learning algorithm, with a mean pixel accuracy and mean intersection of union values of the algorithm of 0.95 and 0.77, and precision and recall of 81% and 95%, respectively. The time for detection is less than 5 minutes

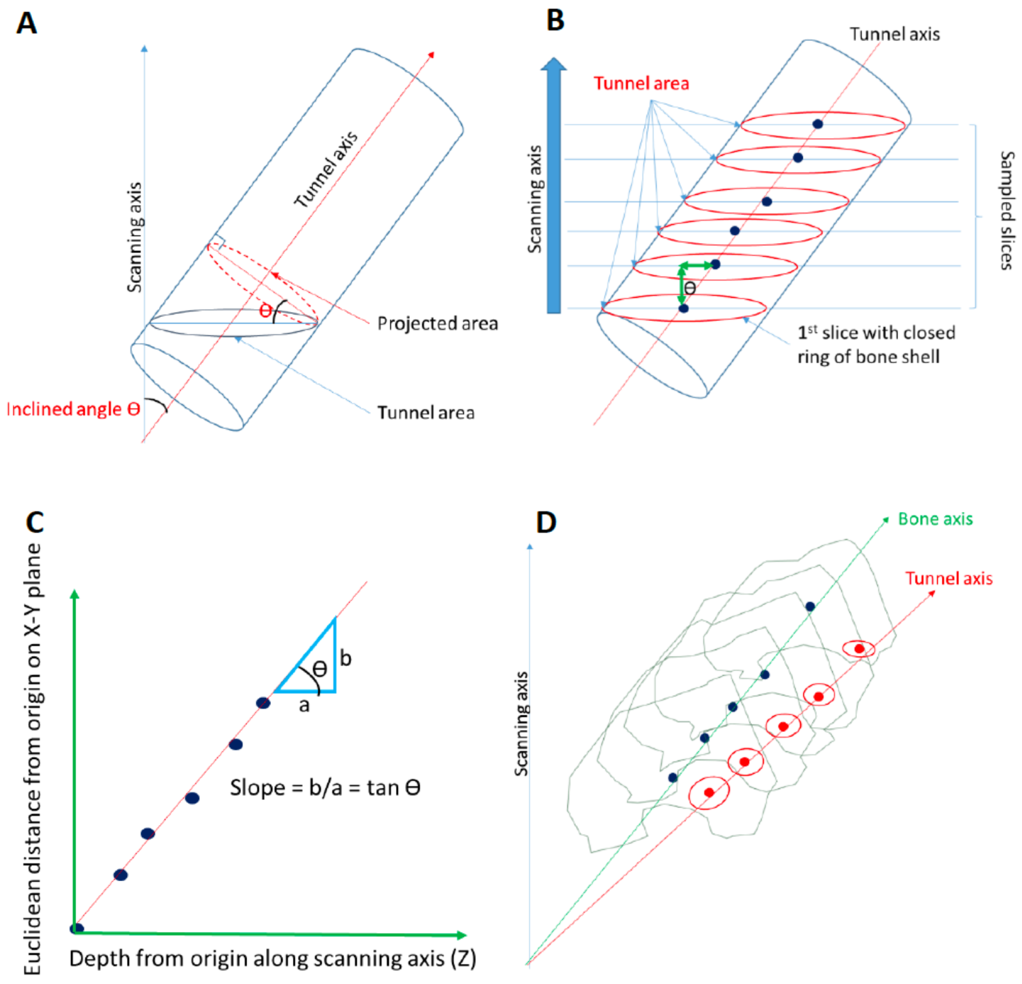
# Discussion

- U-Net is a convolutional network architecture for fast and precise segmentation of images without human supervision






Calculation of projected tunnel area according to the inclined angle between scanning axis and tunnel axis

# Conclusion

- Measurement of bone shell formation by high resolution CT is potentially useful to assess bone tendon junction healing after ACLR.

- Further development on the machine learning model may eventually help clinical follow-up.

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