4 D kinematic Computed Tomography for Musculoskeletal Assessment: Clinical Applications, Technical Considerations, and Future Directions

Amit Kumar[1], Monika[2]
[1]*Tutor Technologist, PGIMER, Chandigarh*
[2] *Senior Technologist, PGIMER, Chandigarh*

Abstract: Four-dimensional computed tomography (4DCT), also referred to as dynamic CT or kinematic CT enables the visualization and quantitative assessment of anatomical motion over time. Unlike conventional CT, which generally provides a static representation of anatomical structures, 4DCT generates a series of volumetric datasets acquired at multiple time points during movement and provides cine loop for motion assessment This capability has expanded the role of CT in the assessment of joint kinematics, instability, impingement, maltracking, and other dynamic musculoskeletal disorders. Recent developments in wide-detector arrays, large coverage, rapid gantry rotation, image reconstruction algorithms, deep learning algorithm enables radiation-dose reduction have facilitated the clinical application of 4DCT. The technique has been used to evaluate the wrist, elbow, shoulder girdle, foot and ankle, knee, hip, and temporomandibular joint. In many cases, some findings remain undetected on static radiographs, conventional CT, or magnetic resonance imaging. But it can be demonstrated well by using 4DCT. The information obtained may improve diagnostic accuracy, support prognostic assessment, guide surgical planning, and assist in evaluating treatment outcomes.

In spite of these advantages, several challenges remain, including radiation exposure, motion artifacts, limited field of view, limited movement because of CT bore size and the absence of standardized motion, reproducing motion inside gantry is challenging, research is focused on developing motorized jigs to ensure repeatable, controlled patient movement analysis protocols. Future improvements in detector technology, dose optimization, motion correction, and reconstruction algorithms are expected to increase the safety, reproducibility, and clinical utility of 4DCT.

Keywords four-dimensional computed tomography, dynamic CT, kinematic CT, musculoskeletal imaging, joint instability, motion analysis, image quality, radiation dose.

Introduction: Four-dimensional computed tomography (4DCT) is an emerging imaging technique which has important applications in both diagnosis and treatment planing. The technique allows anatomical structures to be examined across multiple time points during movement, thereby providing a dynamic representation of joint movements. Through the acquisition of sequential three-dimensional CT volumes, the position and movement of bones and joints can be assessed throughout a selected range of motion.1,28,29. The principal advantage of 4DCT is that it permits the direct assessment of movement rather than relying solely on static anatomical imaging. This is particularly valuable in which symptoms are produced by movement, instability, impingement, abnormal tracking, or transient subluxation. Conventional radiography and static CT may demonstrate bone morphology but may not reveal the precise mechanical event responsible for a patient's symptoms. Although magnetic resonance imaging provides excellent soft-tissue contrast, it may also fail to demonstrate abnormalities that occur only during active movement.1**.** The clinical application of 4DCT is not restricted to joint imaging or orthopaedic assessment. The technology may also be applied to other anatomical and functional systems in which motion plays a significant diagnostic role.1 However, its current clinical development has been particularly prominent in musculoskeletal imaging because of the need to understand complex joint kinematics and dynamic mechanical abnormalities.

Developments in Four-Dimensional CT

The use of 4DCT has increased substantially following the introduction of large coverage by detector arrays and ultrafast gantry rotation. These technological developments allow the same anatomical volume to be scanned repeatedly during a single movement or functional task. The resulting image series represents the position of the patient's anatomy at successive time points, thereby creating a kinematic volume.1 In a typical 4DCT examination, the patient is instructed to perform a specific movement, such as flexion, extension, rotation, or loading of a joint. Sequential volumetric datasets are then acquired while the joint moves through the desired range. The individual datasets can subsequently be reviewed as a cine sequence or processed using specialized software to quantify translation, rotation, displacement, and changes in joint alignment. The increasing availability of multidetector CT systems has improved temporal and spatial resolution. In addition, modern dose-reduction strategies, model based or deep learning iterative reconstruction methods have helped to reduce radiation dose. Nevertheless, the radiation burden must be carefully considered, particularly when the examination involves radiosensitive organs or repeated follow-up imaging.

Musculoskeletal Applications

Hand and Wrist: Carpal movements can be evaluated extensively using 4DCT. The wrist has a complex anatomy composed of multiple small bones and articulations, even minor alterations in carpal alignment may result in considerable functional deformities and pain. In some patients, the mechanical origin of symptoms can be demonstrated only during movement. Without this information, accurate diagnosis and appropriate treatment may be difficult.1. Conventional imaging techniques, including radiography and MRI, may not provide sufficient information for detecting abnormalities in carpal movements. The small field of view required for wrist imaging, together with the relatively low radiation sensitivity of the wrist, makes this region particularly suitable for 4DCT. The technique has therefore been used to examine carpal instability, altered intercarpal relationships, and changes in wrist biomechanics before and after surgical repair.1,2,3,4**.** Dynamic wrist imaging can provide both qualitative and quantitative information. Translation and rotation of individual carpal bones may be measured throughout the range of motion. These measurements may improve the characterization of ligamentous injury and assist in determining the success of surgical stabilization.

Elbow: Four-dimensional CT has important applications in the assessment of elbow motion. Dynamic imaging can identify impingement caused by osteophytes involving the coronoid process or olecranon. Such bony abnormalities may prevent terminal flexion or extension and may contribute to persistent restriction. The principal benefit of 4DCT in this setting is that it can demonstrate whether the restriction is mechanical and is caused by osseous impingement, rather than being the result of capsular fibrosis or soft-tissue adhesions. This distinction is clinically important because the treatment strategy differs according to the underlying cause. While bony impingement may be treated by removing the obstructing osteophyte, capsular contracture may require soft-tissue release or rehabilitation. Further investigation of elbow kinematics using 4DCT is warranted.6.

Shoulder Girdle: The shoulder joint examined dynamically using 4DCT, including the sternoclavicular joint, acromioclavicular joint, and scapulothoracijoint. These applications are important in patients with shoulder instability, unexplained pain, impingement, or abnormal scapular movement. Dynamic 4DCT has been used to image posterior translation of the medial clavicle, with contact against the trachea while movement, in a patient who experienced intermittent choking. This abnormality was not demonstrated on conventional CT or MRI.1. The dynamic imaging contributed to the decision to perform surgical stabilization, which resulted in a favourable clinical outcome. In addition, dynamic C T can used to quantify sternoclavicular joint instability by measuring translation during active arm movement. This information may help clinicians in selecting between operative and conservative management.1,6. The acromioclavicular joint can also be evaluated

during dynamic movement. In patients with persistent pain after low-grade injury, 4DCT has demonstrated unexpectedly large translations during glenohumeral movement. These findings provide accurate information of functional impairment and may help predict the potential benefits of reconstructive surgery.7,8. Dynamic imaging has additionally provided reference data regarding normal acromioclavicular joint motion. This information can be used to compare movements and may identify pathological movement in patients whose conventional CT findings are not helpful, particularly in case of instability and arthrosis.7,8. Four-dimensional CT has also been applied to patients with snapping scapula syndrome where scapula impinges on the posterior ribs, preoperative dynamic imaging can identify the exact location of contact. This provide imaging for more accurate surgical planning and increases the probability that the actual site of pathology will be treated.1,9. Collectively, these applications demonstrate that 4DCT can improve diagnostic evaluation, prognostic assessment, and surgical planning throughout the shoulder girdle.

Foot and Ankle: The subtalar joint has been examined by dynamic CT in both healthy individuals and patients with chronic ankle instability or joint stiffness. Dynamic imaging explained differences in subtalar movement between asymptomatic ankles and those affected by chronic instability or restricted motion.1,10. After external stress is applied to the ankle which moves through a prescribed range, 4DCT can provide an objective assessment of the mechanical basis of instability. This is an important advantage over static imaging.10. The technique may evaluate the response to treatment. Manipulations in movement patterns can be monitored following conservative management or surgery, and specific kinematic abnormalities may be associated with particular injury patterns. This may allow treatment to be tailored more precisely to the individual patient.11. movements at the tibiofibular joint, commonly referred to as the ankle syndesmosis, has also been demonstrated by using this technique. Evaluation of syndesmotic motion may be clinically helpful in patients with suspected ligamentous injury, chronic instability, or persistent symptoms following ankle trauma.12

Knee: 4D kinematic CT has important role to evaluate patellar tracking throughout knee movement. Prescribed protocols have been used primarily in patients with patellofemoral pain syndrome, patellar instability, maltracking, and subluxation.13,14,15. The articulation between the patella and trochlear groove changes continuously during knee flexion and extension. In contrast, static imaging may not accurately represent the position of the patella during knee movements. Four-dimensional kinematic CT is the technique which provide repeated three-dimensional measurements throughout the complete range of motion. Tanaka and colleagues reported that the tibial tubercle–trochlear groove distance changed significantly with the angle of knee flexion. This variation was not uniform when assessed using conventional static imaging. Based on accepted tibial tubercle–trochlear groove thresholds, 70% of symptomatic patients would have qualified for tibial tubercle osteotomy when the knee was positioned at 30° of flexion, whereas only 24% would have met the criteria when the knee was positioned at 0°.16,17,18,19. These findings demonstrate the importance of joint position during evaluation. By providing dynamic and reproducible assessments of patellar instability and maltracking, 4DCT plays important role to explain cause of patellofemoral pain and assist in selecting suitable surgical or conservative treatment.

Hip: limited use of 4 d kinematic C T is has been observed as it exhibits comparatively large amount of radiation dose. Higher effective radiation dose associated with imaging the pelvis and hip, the proximity of radiosensitive organs, and the greater exposure required to obtain optimum image quality.20,22., 4DCT has important role in demonstration in the evaluation of femoroacetabular impingement. Wassilew and colleagues reported that 4DCT could predict the location of cam- and pincer-type impingement involving the femur and acetabulum more accurately than static imaging. when compared with surgical hip dislocation as the reference standard.22. Dynamic demonstration of the hip may provide valuable information for minimally invasive surgical planning. To see the precise location of impingement, surgeons may be able to remove the abnormal contact area more accurately during hip arthroscopy. This may reduce arthroscopy time,

decrease surgical morbidity, and improve the precision of the required bone resection. Further research is required for development of low-dose acquisition protocols, improved detector systems, and advanced image-reconstruction techniques will be essential for reducing radiation exposure and increasing the image quality.

Temporomandibular Joint: Four-dimensional CT is a relatively novel technique for evaluating the biomechanics of the temporomandibular joint (TMJ). It may provide information that cannot be obtained using static imaging in CT or MRI, especially when abnormalities occur during mastication or mandibular movement. The technique has been used to investigate the possible mechanical causes of TMJ osteoarthritis (TMJ-OA). During analysis of coronal motion, repeated friction was observed between the articular surface of the diseased mandibular condyle and the articular eminence during normal mastication.23,24,25. friction during mastication between the joint surfaces is considered an important cause for development of internal derangement and degenerative disease of the TMJ. Dynamic 4DCT may therefore plays crucial role to identifying abnormal contact and may improve understanding of the relationship between joint motion, mechanical loading, and osteoarthritic changes. The ability to visualize repeated friction in a moving joint represents a significant advantage over static imaging.

Technical Challenges and Future Directions

Although 4DCT offers substantial diagnostic values, several technical and clinical challenges must be addressed before the technique can be adopted.

Radiation Dose: comparatively 4 D dynamic C T involves more radiation dose as it requires multiple volume acquisition. Hence, Dose optimization is therefore essential. Protocols should be designed to achieve the lowest reasonable radiation dose while maintaining adequate image quality in term of spatial and temporal resolution for accurate motion tracking. Dose-reduction may achieve by lowering tube current, optimizing tube voltage, limiting the scan range, using automated exposure control, and applying iterative or model-based reconstruction algorithms. Deep learning reconstruction algorithm provides substantial amount of radition dose reduction. The potential benefits of dynamic imaging should always be balanced against the associated radiation risk, particularly when the hip, pelvis, or other radiosensitive regions are examined.27,28

Field of View and Detector Technology: increase detector width cover a sufficiently large anatomical region. Wider detector arrays can improve volumetric coverage and permit the acquisition of larger anatomical regions during a single gantry rotation. Increasing the number of detector rows or enlarging detector dimensions may therefore improve the application of 4DCT to complex joint systems.27,28**.** However, wider coverage must be accompanied by adequate spatial resolution and consistent image quality. Future detector technologies may improve the balance between anatomical coverage, temporal resolution, radiation dose, and image sharpness.

Motion Artefacts: Motion artefact remains a major limitation of dynamic CT. Irregular; abrupt patient movement can produce motion related artifacts and diminishes image quality and effect with the accurate registration of sequential volumes. Artefacts may also occur when the movement is not aligned optimally with the acquisition plane. Several approaches have been recommended to reduce motion artefacts. The plane of motion should be positioned appropriately, and patients should be trained before the scan. External auditory or visual cues may be used to promote smooth, reproducible movement. In selected cases, custom devices may be used to limit the range of motion or simulate weight-bearing conditions.27,28

Standardization and Quantitative Analysis: standardization of protocol is required to make 4d dynamic C T reliable. These protocols should be specific for patient position, movement, scanning parameters, reconstruction algorithm, and quantitative analysis technique, radiation-dose limits. Image-processing software may improve the reproducibility of measurements. Parameters such as translation, rotation, joint-space change, contact position, and angular displacement should be defined consistently.

Future Research

Future research should focus on advanced image reconstruction, use of artificial intelligence for

enhanced image quality and radiation dose reduction, automated segmentation, and biomechanical modelling. Machine-learning algorithms may assist in identifying abnormal movement patterns and may facilitate the rapid analysis of large dynamic datasets. Multimodality studies combining 4DCT with MRI, ultrasound, or motion-capture systems may also provide a more comprehensive assessment of both osseous and soft-tissue movement. prospective research is required to determine whether 4DCT findings improve patient outcomes, more accurate diagnosis, precise treatment planning and reduce unnecessary surgical intervention.

Conclusion: Four-dimensional computed tomography is an innovative, evolving imaging technology that provides dynamic visualization and quantify assessment of musculoskeletal movements. By acquiring multiple volumetric datasets during movement, it can demonstrate instability, maltracking, impingement, subluxation, and abnormal joint contact that may not visualised on static imaging.

The technique has demonstrated clinical and research applications in the wrist, elbow, shoulder girdle, foot and ankle, knee, hip, and temporomandibular joint. In addition to improving diagnosis, 4DCT may contribute to prognostic assessment, treatment planning, evaluation of surgical candidates, and postoperative outcome analysis.

Despite its potential, limitations related to radiation exposure, motion artefact, field of view, and protocol standardization must be addressed. Continued advances in detector technology, low-dose acquisition, iterative reconstruction algorithms, automated image analysis, and artificial intelligence are expected to improve both diagnostic performances. As these developments progress, 4DCT may become an increasingly valuable tool for demonstrating joint kinematics and providing information to management of musculoskeletal disorders.

References

1. Wong, M. T., Wiens, C., Kuczynski, M., Manske, S., & Schneider, P. S. (2022). Four-dimensional computed tomography: musculoskeletal applications. Canadian journal of surgery. Journal canadien de chirurgie, 65(3), E388–E393. https://doi.org/10.1503/cjs.023420

2. Zhao K, Breighner R, Holmes D, et al. A technique for quantifying wrist motion using four-dimensional computed tomography: approach and validation. J Biomech Eng 2015;137:074501.

3. Shores JT, Demehri S, Chhabra A. Kinematic "4 dimensional" CT imaging in the assessment of wrist biomechanics before and after surgical repair. Eplasty 2013;13:e9
4. Leng S, Zhao K, Qu M, et al. Dynamic CT technique for assessment of wrist joint instabilities. Med Phys 2011;38:S50.

5. Wassilew GI, Janz V, Heller MO, et al. Real time visualization of femoroacetabular impingement and subluxation using 320-slice computed tomography. J Orthop Res 2013;31:275–81

6. Goh YP, Lau KK. Using the 320-Multidetector computed tomography scanner for four-dimensional functional assessment of the elbow joint. Am J Orthop (Belle Mead NJ) 2012;41:E20–4

7. Goh YP, Kamali Moaveni A, Hoy G, et al. Dynamic assessment of sternoclavicular joint instability using four-dimensional computed tomography. J Med Imaging Radiat Oncol 2019;63:216–21

8. Dyer DR, Troupis JM, Kamali Moaveni A. Wide field of view CT and acromioclavicular joint instability: a technical innovation. J Med Imaging Radiat Oncol 2015;59:326–30.
9. Alta TD, Bell SN, Troupis JM, et al. The new 4-dimensional computed tomographic scanner allows dynamic visualization and measurement of normal acromioclavicular joint motion in an unloaded and loaded condition. J Comput Assist Tomogr 2012;36: 749–54.
10. Bell SN, Troupis JM, Miller D, et al. Four-dimensional computed tomography scans facilitate preoperative planning in snapping scapula syndrome. J Shoulder Elbow Surg 2015;24:e83–90.

11. Gondim Teixeira PA, Formery AS, Balazuc G, et al. Comparison between subtalar joint quantitative kinematic 4-D CT parameters in

healthy volunteers and patients with joint stiffness or chronic ankle instability: a preliminary study. Eur J Radiol 2019;114:76–84.
12. Mousavian A, Shakoor D, Hafezi-Nejad N, et al. Tibiofibular syndesmosis in asymptomatic ankles: initial kinematic analysis using four-dimensional CT. Clin Radiol 2019;74:571.e1–8.
13. Gondim Teixeira PA, Formery AS, Jacquot A, et al. Quantitative analysis of subtalar joint motion with 4D CT: proof of concept with cadaveric and healthy subject evaluation. AJR Am J Roentgenol 2017; 208:150–8.
14. de Sá Rebelo M, Moreno RA, Gobbi RG, et al. Description of patellar movement by 3D parameters obtained from dynamic CT acquisition. Proc SPIE Int Soc Opt Eng 2014;9035. 10.1117/12.2043677.
15. Forsberg D, Lindblom M, Quick P, et al. Quantitative analysis of the patellofemoral motion pattern using semi-automatic processing of 4D CT data. Int J Comput Assist Radiol Surg 2016;11:1731–41.
16. Tanaka MJ, Elias JJ, Williams AA, et al. Characterization of patellar maltracking using dynamic kinematic CT imaging in patients with patellar instability. Knee Surg Sports Traumatol Arthrosc 2016;24: 3634–41
17. Tanaka MJ, Elias JJ, Williams AA, et al. Characterization of patellar maltracking using dynamic kinematic CT imaging in patients with patellar instability. Knee Surg Sports Traumatol Arthrosc 2016;24: 3634–41.
18. Tanaka MJ, Elias JJ, Williams AA, et al. Correlation between changes in tibial tuberosity–trochlear groove distance and patellar position during active knee extension on dynamic kinematic computed tomographic imaging. Arthroscopy 2015;31:1748–55
19. Demehri S, Thawait GL, Williams AA, et al. Imaging characteristics of contralateral asymptomatic patellofemoral joints in patients with unilateral instability. Radiology 2014;273:821–30.
20. Williams AA, Elias JJ, Tanaka MJ, et al. The relationship between tibial tuberosity–trochlear groove distance and abnormal patellar tracking in patients with unilateral patellar instability. Arthroscopy 2016;32:55–61
21. Biswas D, Bible JE, Bohan M, et al. Radiation exposure from musculoskeletal computerized tomographic scans. J Bone Joint Surg Am 2009;91:1882–9
22. Wassilew GI, Janz V, Heller MO, et al. Real time visualization of femoroacetabular impingement and subluxation using 320-slice computed tomography. J Orthop Res 2013;31:275–81
23. E. Tanaka, M.S. Detamore, L.G. MercuriDegenerative disorders of the temporomandibular joint: Etiology, diagnosis, and treatment J Dent Res, 87 (2008), p. 296.
24. E. Tanaka, N. Kawai, M. Tanaka, et al.The frictional coefficient of the temporomandibular joint and its dependency on the magnitude and duration of joint loading. J Dent Res, 83 (2004), p.
25. J.C. Nickel, L.R. Iwasaki, D.E. Feely, et al.The effect of disc thickness and trauma on disc surface friction in the porcine temporomandibular jointArch Oral Biol, 46 (2001), p.
26. History of cardiac computed tomography: single to 320-detector row multislice computed tomography GS Hurlock, H Higashino, T Mochizuki - The international journal of …, 2009 – Springer.
27. Musculoskeletal wide-detector CT kinematic evaluation: from motion to image PAG Teixeira, A Gervaise, M Louis… - Seminars in …, 2015 - thieme-connect.com
28. CT coronary angiography: 256-slice and 320-detector row scannersEM Hsiao, FJ Rybicki, M Steigner - Current cardiology reports, 2010 - Springe