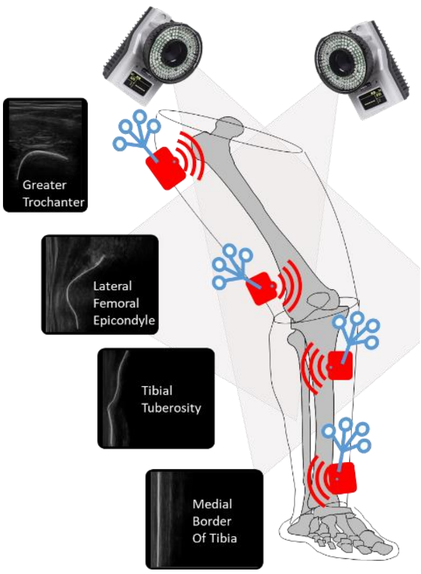
UltraMotion: An innovative approach to measure 4D *in vivo* bony segment motions based on the fusion between ultrasound and motion capture systems

1. Summary



In clinical settings, **human movement analysis** has become an essential tool to **identify, characterise and follow the evolution of the locomotor system pathologies**, as well as to **assess the efficacy of a rehabilitation program or a surgery**. Classically, this approach relies on the measurement of the 3D trajectories of a set of reflective skin markers by the mean of an optoelectronic system. The position and orientation of bony segments is then estimated during a movement using these trajectories.

However, the relative motion between the cutaneous markers and the underlying bones, known as **soft tissue artefacts** (STA), introduces significant errors that **limit the accuracy of the measurements**, especially when considering small rotations and displacements. Still, an accurate joint kinematics estimation is **crucial to properly identify and quantify pathology-related movements' abnormalities**. Gaining access to such information would open new possibilities for the evaluation, treatment and follow up of patients.

To date, researchers have been using intra-cortical pins or bi-plane fluoroscopy to tackle the issue of STA. However, these solutions are very invasive or irradiating and cannot be used in clinical settings for ethical reasons. Thus, there is a need for the development of new technologies allowing an accurate measurement of joint kinematics. **Another solution to tackle STA is the fusion of ultrasound (US) imaging with traditional motion capture**. The fusion method consists in calibrating the US transducer in such a way that the position of each point of the US plane can be measured in space. Hence, by combining multiple images of the same bone it is possible to reconstruct its position and orientation in space and to **cancel STA**.

Recently, the proof of concept of using A-mode US for the motion capture of the lower limb was made and B-mode US was used to track the greater trochanter. The outcomes of these studies are promising but the **feasibility of such approaches in clinical settings have not been assessed** and these devices were **not validated *in vivo***.

Our project thus aims to achieve the fast prototyping and testing of an innovative system allowing the **fusion of B-mode ultrasound and marker-based motion capture** to track the **knee kinematics** during gait. This system will be composed of two calibrated US transducers per segment (one proximal, one distal) allowing the bone pose reconstruction of the femur and tibia segments, and thus the measurement of the knee kinematics. **It will be validated *in vivo*** and its **applicability in clinical settings will be evaluated**.

2. Research Plan

In clinical settings, **human movement analysis** has become an essential tool to **identify, characterise and follow the evolution of the locomotor system pathologies**, as well as to assess the **efficacy of a rehabilitation program or a surgery**. The goal of such analysis is to provide an accurate measure of bones and joints movements during various tasks to **identify and quantify abnormalities** in patients with various pathologies of the neuromusculoskeletal system (*e.g.* cerebral palsy, osteoarthritis) to **help in the clinical decision making**. With such measurements, one can estimate joint kinematics, joint forces and muscle forces with biomechanical models.

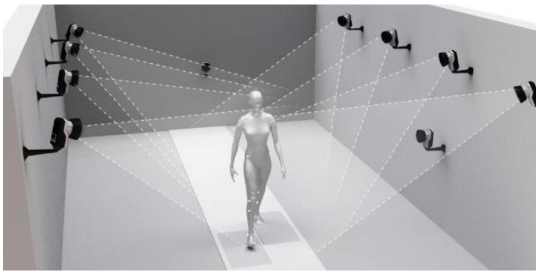


Fig. 1 - Illustration of an optolectronic cameras set-up

Human movement analysis classically relies on the measurement of the **3D trajectories of a set of reflective skin markers** by the mean of an optoelectronic system (Fig. 1). The position and orientation of each bony segment is estimated from these trajectories. However, the relative motion of the skin markers and underlying bones, known as **soft tissue artefacts (STA)**, introduces significant errors that limit the accuracy of the measurements, especially when considering small movements (rotations and displacements). As an example, STA-related errors of the thigh and shank has the same magnitude as knee displacements during gait (Leardini et al., 2005). **An accurate joint kinematics estimation is crucial to properly identify and quantify pathology-related movements' abnormalities**. Gaining access to such information would open new possibilities for the evaluation, treatment and follow up of patients.

To date, researchers have been using intra-cortical pins (Reinschmidt and Van Den Bogert, 1997) or bi-plane fluoroscopy (Benoit et al., 2006; Lu et al., 2008) to tackle the STA issue. However, **these solutions are invasive or irradiating** and cannot be used in clinical settings for ethical reasons. Thus, there is a need for the development of new technologies allowing an accurate measurement of joint kinematics. **A solution relies on the use of ultrasound (US) imaging coupled with traditional motion capture systems**. This method consists in calibrating an US transducer in such a way that the position in space of each point of the US plane can be measured. By registering (*i.e.* fitting) multiple US images of the same bony landmark to the full geometry of the bone, it is possible to reconstruct its position and orientation in space and to cancel STA.

2.1. Current state of research in the field

The **proof of concept** of using A-mode US (Niu, 2018) and B-mode US (Jia et al., 2017; Masum et al., 2014) for the motion capture of the lower limb has been done recently.

A-mode US gives a 1D information that can measure the distance between the transducer and a point of the bony segment (Fig. 2). By coupling 15 transducers per segment, Niu et al. were able to estimate the position and orientation of the femur and tibia during treadmill gait (Niu, 2018). This approach was validated *ex vivo* on one knee and showed an accuracy of 1.06 ± 2.05° for rotations and -2.16 ± 3.02 mm for translations. These promising results show that **US is a strong candidate to tackle STA**. However, A-mode US requires that the transducers remain perpendicular to the bone surface. This is challenging during a dynamic task such as gait. Indeed, the STA will make the transducer move which will change the direction of the soundwave, the bone may also move out the US transducer field of view. Furthermore, ***in vivo* validation was not done**.

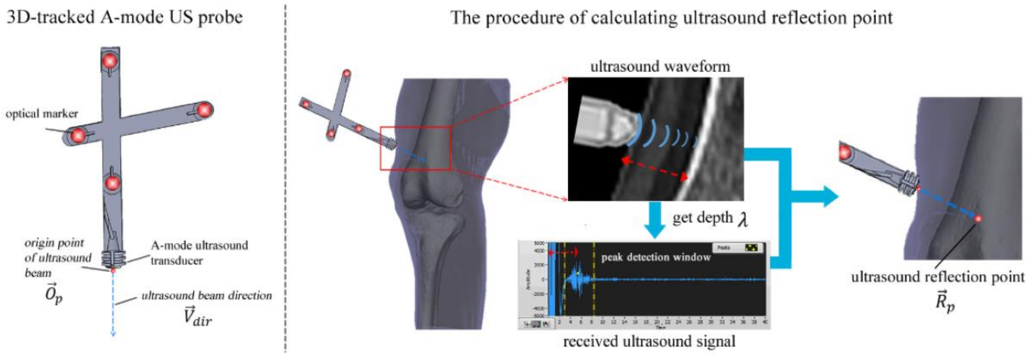


Fig. 2 – Principle of calculating the US reflection point on the bone surface using A-mode US (adapted from (Niu, 2018)*)*

B-mode US gives a 2D image that shows soft tissues and bones. Bones are identified by a high intensity border on the image and by a “shadow” after this border (Hacihaliloglu, 2017). Thus, they can be easily recognised and automatic segmentation algorithms are being developed with good results (Hacihaliloglu, 2017). Masum et al. (Masum et al., 2014) presented a proof of concept of the measurement of knee kinematics with 6 B-mode US transducers. Three transducers per bony segment were placed on “H” structures to track saw bones femur and tibia in a water tank (Fig. 3).

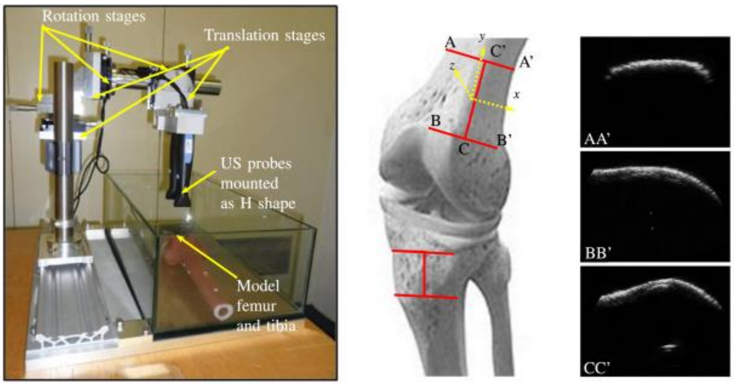


Fig. 3 - Illustration of the B-mode US transducers set-up used to track saw bones femur and tibia (adapted from (Masum et al., 2014)*)*

This approach demonstrated a **precision lower than 1 mm for displacements and lower than 1 degree for joint angles** (Masum et al., 2014). This study proved that B-mode US is also a good candidate to measure the knee motion. However, to the best of our knowledge, **it has not been yet tested *in vivo* nor *ex vivo***. Jia et al. (Jia et al., 2015) tested successfully the tracking of the greater trochanter *in vivo* during treadmill gait with B-mode US but their estimation of joint kinematics (Jia et al., 2016) still depends on skin marker and is thus subject to STA.

2.2. Project description

2.2.1. Goal of the project

This project aims to **develop an experimental non-invasive and non-irradiating motion capture system that compensate STA and is adapted to clinical setting**. This will be obtained by the **fusion of B-mode US and marker-based motion capture to track joint kinematics during gait**. As **proof of concept**, this approach will be tested on knee kinematics, a joint highly impacted by STA (Peters et al., 2010). Our system will be composed of two calibrated US transducers (one proximal, one distal) per segment (femur and tibia). It will allow the bone pose reconstruction of these bony segment and thus the measurement of knee kinematics. **This approach will be validated *in vivo*** on healthy participants during gait and **its applicability in clinical settings will be evaluated** on patients with knee osteoarthritis during gait.

2.2.2. Methodology

Approach of the project

Our approach requires the following steps (Fig. 4): 1) Measurement of the 3D pose of the US transducers using a motion capture system, 2) Segmentation of bony landmarks on US images, 3) Reconstruction of the 3D bony landmarks position (data fusion 1), 4) The measurement of bone geometry with medical imaging, and 5) the Registration (fitting) of the bone geometry on the 3D bony landmarks position (data fusion 2). After bones registration, the 3D joint kinematics can be estimated.

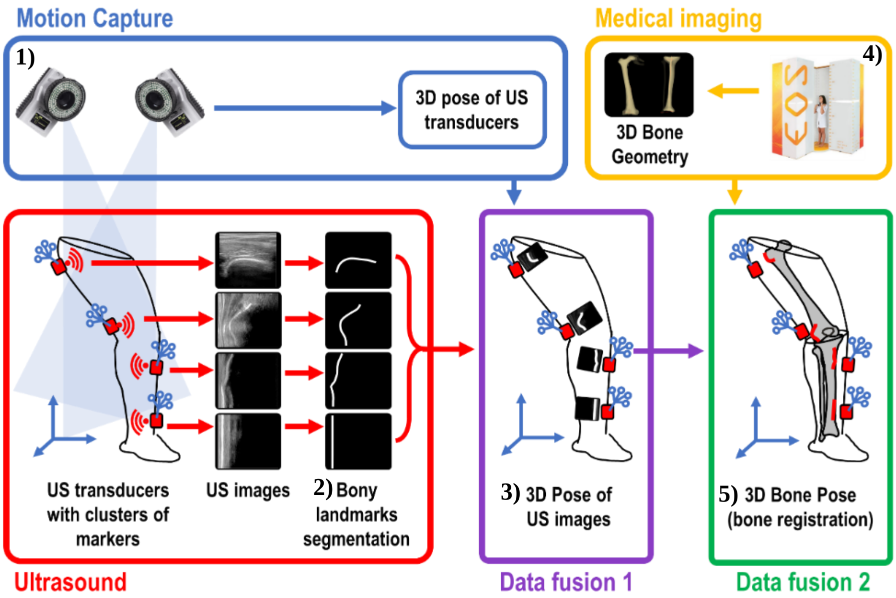


Fig. 4 – Workflow of the project

Material and method

The pose of the US transducers will be measured by a 12 cameras optoelectronic system (Oqus7+, QTM 2019, Qualisys, Göteborg, Sweden) available at the University Hospital of Geneva. Four US transducers (LV8-5L60N-2, Telemed, Vilnius, Lithuania) will be used. The bone segmentation will be done manually for this project, but we plan to automate this step with machine learning (Salehi et al., 2017) and advanced segmentation algorithm (Hacihaliloglu, 2017; R. Jia et al., 2016) in the future. Bone geometries will be obtained with low-dose bi-plane X-rays (EOS Imaging Inc., Paris, France) for the patients and from scaled generic models for healthy participants (Ackerman, 1991). Standard fitting algorithms will be applied for the bone registration (Oliveira and Tavares, 2014). **The main developments will be on the setup of the US transducers**, *i.e.* the fastening and optimal positioning of the US transducers on the thigh and shank, the clusters of markers to measure the pose of the US transducers and the calibration of the US transducer plane in the measurement volume. The fastening devices and clusters of markers will be designed with CAD and manufactured through 3D printing. We plan to use the agile development principle by testing the device with healthy participants and patients along the design process to improve the prototype with user experience.

Validation

The gold-standard validation would be a measurement against intra-cortical pins that could be performed in the operating room before a total knee replacement surgery performed with surgical navigation tools. Our team have existing collaborations with the orthopaedic department of the University Hospitals of Geneva, but this type of measurement is sensitive and might not be feasible or be accepted by the local ethics committee for a proof od concept. Thus, **our approach will be validated during gait against the KneeKG** (Emovi Inc., Montréal, Quebec, Canada), a silver-standard measurement system dedicated to knee kinematics (Hagemeister et al., 2005). Five healthy participants and five patients with knee osteoarthritis will participate in the study. Depending on the outcome of this silver standard validation, the gold standard could be taken into consideration for future research.

Feasibility criteria

To assess the **feasibility of using this approach in clinical settings**, we identified 4 primary criteria: 1) the time to equip the patient with US transducers should not add more than 10 minutes, 2) the device should not modify the natural movement of the patient nor be a source of pain, 3) the data should be able to be processed by motion capture laboratory staff, 4) the cost for such additional devices must remain reasonable.

2.2.3. Expected outcome

The goal is to reach an error lower than 5 degrees of deviation with joint angles measured by the KneeKG during gait. This threshold has been defined by McGinley et al. (McGinley et al., 2009) has the maximum error before impacting clinical interpretations.

2.2.4. Schedule of the project

		M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12
US measurements procedure	Optimal placement Clusters and fastening 3D Calibration												
Testing	Healthy participants Knee OA patients												

2.3. Risks and gains of the research project

The **first risk** would be a poor image quality that would require the development of advanced tools for image processing (Perdios et al., 2018). However, the previous proof of concept performed using B-mode US are encouraging (Masum et al., 2014). The **second risk** would be a difficulty to include patients in the study. This risk is low since we work closely with orthopaedic surgeons and we only require a small sample to make the proof of concept. The **last risk** is to fail having an error below 5 degrees. This risk is low when considering the previous work on A-mode (Niu, 2018) and B-mode US (Masum et al., 2014).

The **main gain is to remove STA in clinical settings** with a non-invasive and non-irradiating approach. This will be **beneficial to the patients** and will give access to accurate joint kinematics which will **improve diagnosis, treatment selection and patient follow up**. The **future developments** of this approach will be to **test it on a larger number of patients** and on patients with **other pathologies** (*e.g.* cerebral palsy), to apply it to **other joints** and to develop links with model of joint dynamics and of the neuromusculoskeletal system.

2.4. Short budget description

The requested budget is reported in the following table and mainly corresponds to the salary of a 60% postdoc during 12 months (to be hired) and the ultrasound system needed for this proof of concept.

	Quantity	Unitary cost	Total cost
Postdoc (12 months, 60%)	7,2 PM	7.700 CHF	59.040 CHF
Ultrasound system	1	40.000 CHF	36.000 CHF
Consumables	1	1.200 CHF	1.500 CHF
International congress	2	1.600 CHF	3.200 CHF
Overhead	0%	0 CHF	0 CHF
TOTAL			99.740 CHF

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