GAJA - Guided self-Acquisition of Joint ultrAsound images*

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Abstract. People with hemophilia require frequent diagnoses of joint bleeding. This is currently achieved with visits to specialized centers. One possibility is to have a point-of-care acquisition of the ultrasound joint image by the patients themselves, followed by a remote evaluation by the practitioner. However, the acquisition of US images is operator-dependent, so it is unclear to what extent patients can acquire images that are suitable for remote diagnosis. In this paper, we present GAJA (Guided Acquisition of Joint ultrAsound), an application designed to guide the patient in collecting US images of their own joints, which are then transmitted to a medical practitioner. GAJA uses a collaborative interaction approach, in which an expert practitioner collects a reference US image of a specific scan during an in-person clinical visit. Anatomical markers for the target joint are automatically extracted and then used as a reference to guide the patient in properly positioning the US probe.

Keywords: Ultrasound · Guidance · Portable probe · Hemophilia

1 Intro

People with hemophilia can experience joint bleeding that, if not promptly treated, can result in synovial hyperplasia, osteochondral damage, and hemophilic arthropathy [12]. To promptly recognize joint bleeding, hemophilic patients should

* This work was partially supported by the project MUSA – Multilayered Urban Sustainability Action – project, funded by the European Union – NextGenerationEU, under the National Recovery and Resilience Plan (NRRP) Mission 4 Component 2 Investment Line 1.5: Strenghtening of research structures and creation of R&D "innovation ecosystems", set up of "territorial leaders in R&D", and by the Italian Ministry of Health – Bando Ricerca Corrente. The Fondazione IRCCS Ca' Granda Ospedale Maggiore Policlinico is member of the European Reference Network (ERN) EuroBloodNet.

be regularly visited in specialized centers, particularly in the presence of joint aches. The diagnosis of joint bleeding performed in specialized centers is based on a series of medical history questions and an instrumental examination using magnetic resonance (MRI) or ultrasound (US) images [18,11]. Although MRI is considered the gold standard for this diagnosis, it is not always a practical solution due to its high costs, limited availability, and long examination times [17]. Instead, US is known to be highly operator dependent and therefore requires a highly specialized practitioner [2].

One limitation of the current approach is that it is not always possible for the patient to attend frequent visits (*e.g.*, due to the distance from the specialized center). Similarly, frequent and urgent visits can be hard to manage by the specialized center for a number of reasons, including the limited availability of medical personnel and the costs. In order to address these issues, the University of Milan and the Policlinico of Milan are designing a telemedicine system for at-home joint bleeding diagnosis. The idea of the system is that each hemophilic patient is provided with a portable ultrasound probe connected to a portable computer. When necessary, as a routine check or in case of pain, the patient uses the probe to acquire ultrasound images of the joints[4] and sends them through the computer to the specialized center where a medical practitioner remotely assesses the presence of joint bleeding, supported by a CAD tool using techniques already proposed in the literature for this problem [6,10].

One of the main challenges of the system is that the acquisition of ultrasound images is operator dependent, so it is unclear to what extent the patients can acquire images that are suitable for remote diagnosis. This problem has been addressed in the literature with two different approaches: to teach the patients how to acquire the image so that they can repeat the process without additional support [9] or to guide the acquisition in real-time with remote support by a medical practitioner [3]. The limit of the former approach is that patients tend to forget how to acquire the images [1], while the latter approach is time-consuming for the medical practitioners.

To overcome the limitations of existing approaches, this paper presents GAJA (Guided self-Acquisition of Joint ultrAsound images), an application that provides an automated guiding system to support the patient in the acquisition of joint ultrasound images. GAJA is designed to combine the benefits of existing solutions: on one side, it guides the patient in real-time during the acquisition process, on the other side it does not require the practitioner to remotely supervise the acquisition process. Currently, GAJA is a working prototype that supports the acquisition of knee joint ultrasound images.

2 State of the art

The use of portable US imaging systems has been extensively investigated in the literature [13,15,7]. Such devices were initially conceived to allow clinicians

[4] We use the term "patient" to denote the person in charge of acquiring the ultrasound images but actually it can be the patient or a caregiver.

to make diagnoses at point-of-care (*e.g.*, scene of an accident, patient's home). Three approaches have been proposed in the literature.

The first approach is to train the patients so that they can independently acquire US images [9,5,19].A different approach is to rely on teleguidance, meaning that a medical practitioner supports in real-time the patient during US image acquisition. Teleguidance can be provided by the medical practitioner that observes the US feed (as in [3,16]), possibly combined with the video from other cameras [16]. In [4], the authors suggest that 5G technologies will play a major role to make teleguidance practical in real-world scenarios, and indeed several research groups are exploring it in the general medical domain [3,16]. One limitation of teleguidance is that it requires the availability of human experts to remotely support the patients in performing US scans.

A recent and closely related study compares these two approaches considering the problem of hemophilic patients that use portable probes for self-collection of US images of their joints, with the objective of reducing hospital visits [1]. One of the results of this work is that, even if patients follow a dedicated training session (lasting 4-5 hours), the quality of the self-collected images (without any type of real-time assistance) significantly degrades over time. This suggests that simply training the patients is not sufficient for high-quality self-imaging. Interestingly, this work also shows that high-quality images can be self-collected when patients were assisted with teleguidance (*i.e.*, with human operators remotely assisting the patients). However, the problem analysis conducted in our study uncovered that this solution is impractical in our scenario because it is considered too time-consuming for medical practitioners.

The third approach is based on automated guidance, meaning that the patient is guided to correctly position the probe by an AI system. Existing works adopt a camera mounted on the probe to locate and guide the probe positioning [8,20]. The proposed system, GAJA, also adopts an automated guidance approach, but it does not require an external camera, and instead, it only uses the feed from the probe.

3 Interaction design

GAJA was designed by a multi-disciplinary research team involving computer scientists and medical practitioners. The *Automate-Guide-Remind* design principle was defined in the process and a collaborative interaction approach was adopted.

3.1 "Automate-Guide-Remind" design principle

Previous papers show that learning to self-acquire US images is difficult and that patients tend to forget how to use and position the probe after some time. We conjecture that this is partially due to the large number of actions that the patient is required to complete and that affect the successful acquisition of US images: the probe positioning on the body, its inclination, the joint flexion, putting the gel on the probe, and setting the probe parameters. To mitigate this problem we introduce the *Automate-Guide-Remind* design principle. According to this principle, as many actions as possible should be **automated** so that the patient is not in charge of them. The actions that cannot be automated, and that require extensive practice and deep domain knowledge, which usually only medical practitioners acquire during their training, should be **guided**, meaning that the system should provide automatic instructions in real-time on how to use the system. For the remaining actions, which cannot be automated or guided, clear **reminders** should be automatically provided by the system. These actions should only include those that are easy to explain to the patient and that the patient can easily complete.

To implement the *Automate-Guide-Remind* design principle we identified the set of all actions required to successfully acquire a US image, and divided them into three classes:

- **Automated actions**. This class contains actions that can be totally automated and hence are not in charge of the patient. For example, in GAJA the probe parameters (scan depth and gain) are tuned by the practitioner in a setup phase and saved as presets for each scan. During self-acquisition, these parameters are automatically loaded without intervention by the patient.
- **Guided actions**. These are the actions that the patient does while guided in real-time by the system. In GAJA they include the fine positioning of the probe on the body as well as the exact joint flexion.
- **Reminded actions**. These actions are performed independently by the patient, possibly after initial training and with reminders provided during use. In GAJA these actions include general probe usage (*e.g.*, apply the gel on the probe) as well as scan-specific coarse positioning. For example, in the sub-quadricipital recess (SQR) longitudinal scan the probe should be centered on the leg and parallel to the femur. The patient learns to use the probe and to position it during an initial physical visit with the medical practitioner (the setup step, see Section 3.2). When patients need to use GAJA independently, they can access quick reminders as well as a detailed video explanation (by clicking the 'HELP' button) (*e.g.*, see Figure 1).

Based on this design criterion, in the specific case of the SQR longitudinal scan, we identified two **Guided actions** shown in Figure 2 where the solid orange boxes represent the current patella position, while the dashed boxes represent the target area where the patella should be positioned. Similarly, the purple boxes represent the femur. The two **Guided actions** are: positioning the probe with the correct distance from the knee (see Figure 2a) and flexing the knee to the right angle (see Figure 2b). These actions are particularly important because even small errors can make the acquired US image unsuitable for the diagnosis. In particular, as the probe gets closer to the knee (see Figure 2a left), the patella (rigid orange box in Figure 2a right) moves right in the scan. Similarly, increasing the knee flexion angle (see Figure 2b left) moves the femur down in the scan. We empirically selected these two actions based on the experience of the medical practitioners in our research team.

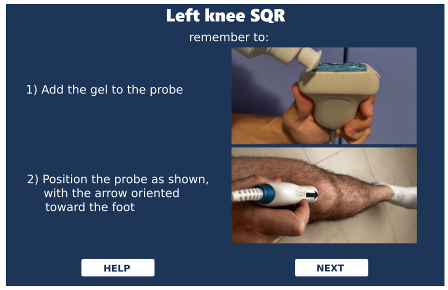
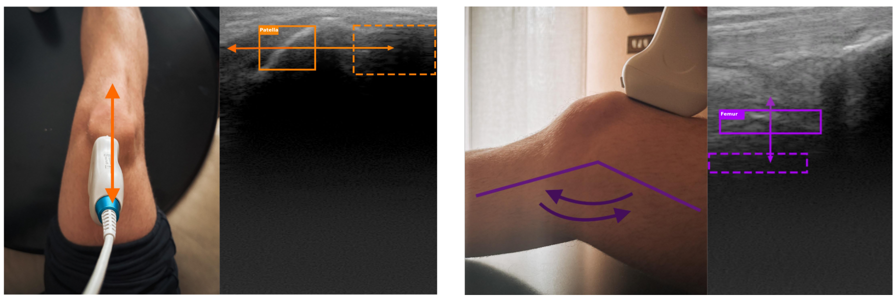


Fig. 1: Instructions provided before the self-acquisition



(a) Probe distance from the knee

(b) Knee flexion

Fig. 2: Effect of moving the probe or the knee angle

3.2 Collaborative interaction approach

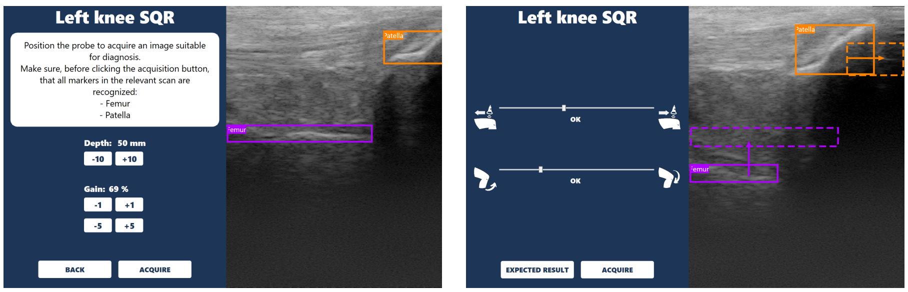
GAJA adopts a collaborative interaction approach between the medical practitioner and the patient. The approach consists of a *setup* step in which the medical practitioner and the patient collaborate in person and a *self-acquisition* step in which the patient independently acquires the image.

Setup step. The setup step is conducted during an in-person clinical visit by an expert medical practitioner who trains the patient (preliminary results show that a training session of about 10 minutes is sufficient) and collects a **reference image** for each target joint scan[5]. The collection of reference images is particularly relevant because the correct probe positioning may vary between patients having different physical characteristics and health conditions, hence it is important to personalize the probe position for each patient.

During the training, the practitioner shows how to use the system and provides basic instructions on how to coarsely position the probe and how to follow the guidance instructions. During the reference image collection, scan-specific

[5] A scan is a specific view of a body part obtained by positioning the probe in a consistent way.

anatomical markers are automatically extracted from the US image using object detection techniques. For example, Figure 3a shows the detected positions of the patella and of the femur in the SQR scan of the knee. The practitioner positions the probe, confirming that the markers are positioned correctly, and acquires a single US image for each scan. While performing this procedure, the practitioner also specifies the scan depth and gain parameters that are stored by GAJA. Note that these parameters should be tuned for each scan and patient.



(a) Setup step by the practitioner (b) Self-acquisition by the patient

Fig. 3: GAJA two-step image acquisition procedure

Self-acquisition step. Self-acquisition requires the patient to complete a set of tasks. First, the target joint to scan is selected from a list, thus loading the probe parameters (**Automated action**). The patient then files a clinical history questionnaire (*e.g.*, does the joint hurt?). Then, a screen containing text indications and images (see Figure 1) reminds the patient to perform **Reminded actions** which include adding the gel on the probe and its coarse positioning.

Next, the patient fine-tunes the probe position through a **Guided action**. The guidance is provided with two simultaneous modalities. On the right side of the interface (see Figure 3b), visual feed from the probe is overlaid with the bounding boxes of the detected anatomical markers present in the feed (continuous border). The patient has to align the anatomical markers with the target areas (with dashed border) of the same color, which are extracted from the reference image collected by the practitioner. For example, in Figure 3b the solid boxes represent the current position of the patella (orange) and femur (purple), while the dashed rectangles represent their position in the reference image.

The left frame provides symbolic indicators of the quality of the current positioning, rendered as sliders, each corresponding to a positioning parameter. Icons at the beginning and at the end of the slider indicate the range of the movements that govern the corresponding parameter. The sliding indicator is centered on the line when the positioning is correct, and it is displaced laterally if the patient needs to perform alignment corrections with respect to that parameter. In the above example, the upper sliding indicator is displaced slightly to the left, indicating that the probe should be approached to the knee.

Once the probe is correctly positioned (see Section 4.2) a message informs the user to hold the probe still for 3 seconds. This was required because we empirically observed that the first acquired images are motion-blurred and requiring the patient to hold the device still mitigates this problem.

We also observe that, although the probe is correctly positioned, it is possible that the acquired image is unsuitable, for example, due to blurriness or lack of gel. However, sending an unsuitable image to the practitioner would result in a delay in the diagnosis process, a loss of time for the practitioner, and in a frustrating user experience for the patient. To mitigate this problem, we adopted two solutions. First, GAJA acquires a set of images (instead of a single one), as this increases the chances that at least one of them is suitable. Second, we use a ML model to check if at least one of the collected images is suitable. Thanks to this model, the user can be immediately informed if no image is suitable and can re-acquire the images. Once a set of images is acquired, they are sent to the server where they are stored for the medical practitioner to use in order to formulate a diagnosis. Note that the larger the set of images sent to the medical practitioners, the longer it could take them for finding a suitable one. In order to speed up the diagnosis process, images are ordered according to the suitability as computed by the ML model, so that the images with the highest likelihood of being suitable can be processed first.

4 Implementation

4.1 Architecture

GAJA was implemented as a Windows application and current prototype runs on *Surface GO3*[6], a touchscreen-based portable device. The device is connected to the portable probe *MicrUS Pro-L40S* manufactured by *Telemed, Lithuania*[7] through a USB-C cable. The application requires bi-directional communication with the ultrasound probe in order to acquire images in real-time and to change the settings (*e.g.*, depth and gain). This was achieved through an SDK made available by the probe manufacturer. Thanks to this solution, the GAJA app can access the ultrasound stream of images in real-time, hence making it possible to locally process the images and show the result in real-time.

The data produced by GAJA (questionnaire answers, images, and other metadata, including the detected bounding boxes, and acquisition time) are transmitted to a remote server, hosted at the hospital, which stores them. The server also hosts a web app that the practitioner can use to visualize the data acquired by various patients through GAJA and to provide the diagnoses.

[6] `https://www.microsoft.com/en-us/d/surface-go-3`
[7] `https://www.telemedultrasound.com/micrus-pro`

4.2 Implementation of machine learning models

GAJA uses two machine learning models: one to detect the anatomical markers, and the other for classifying images suitability.

In order to implement the former model we trained a `YOLO V5`[14] architecture that provides a `nano` version specifically designed to require low memory and provide fast computation also on low-performance devices. Our preliminary results show a mean Average Precision at 0.5 IoU (mAP@0.5) of 0.986 and 0.922 for the patella and femur, respectively. The model was then exported in the *onnx* format to be used in GAJA. The model processing time on the portable device is about 150 milliseconds. Considering the other computations that are required for each frame (e.g., drawing the bounding boxes, acquiring the frame) GAJA is able to process approximately 4 images per second.

The detection model returns, for each processed frame, the bounding boxes of the detected anatomical markers. Since the model can recognize each anatomical marker more than once in each frame, we only consider the prediction for each class with the highest confidence.

The bounding boxes are then displayed as an overlay over the US frame stream. In order to smooth the movements of the bounding boxes as they appear to the user, we adopted a moving average that considers the current and the two previous frames.

Preliminary results suggest that the features that most impact image suitability are the horizontal position of the center of the patella bounding box and the vertical position of the center of the femur bounding box. Hence, for each processed frame, the procedure computes the horizontal distance between the centers of the patella bounding boxes of the current frame and of the reference image. If the distance is smaller than a given threshold, the patella is considered in the correct position. Similarly, GAJA detects if the femur is in the correct position by considering the vertical distance. If both the patella and the femur are in the correct position, then the probe is correctly positioned.

The latter model (classification of image suitability) was implemented as a convolutional neural network based on **InceptionV3**[21]. Our preliminary results show an average `F1-score` of 0.85. In this particular task, the processing time is slower as a result of the model complexity. Hence this model does not run in real-time. The model is currently running on the device but we plan to run it on the server in the future.

5 Conclusions and future work

Portable ultrasound (US) devices have the potential to play a significant role in the context of e-health due to their affordability and non-invasive nature. This is particularly relevant for people with chronic diseases (like hemophilia) that could use self-acquisition to ease the diagnosis process. One of the main factors that are currently limiting the diffusion of this solution is the lack of a practical solution that allows the patient to independently self-acquire suitable images. GAJA addresses this problem, in the specific case of joint US images for hemophilic patients, with a solution that is practical in terms of hardware and software requirements and that appears to be effective in the preliminary experiments we conducted.

The main limitation of this contribution is the lack of formal system validation, in particular from the point of view of its usability by the patient. We are indeed in the process of conducting a user study, aimed at assessing the ability of the system to guide patients in collecting reliable US scans. The two main metrics which we will consider in the evaluation are the time required by the patient to fine-tune the probe position and the percentage of auto-acquisition sessions that contain at least one suitable image (as assessed by a medical practitioner). A longitudinal study will also measure to what extent GAJA can be used by the patients over a long period, as previous works [1] uncovered that it can be challenging for patients to remember how to use the system. We conjecture that, since GAJA adopts the *Automate-Guide-Remind* design principle, it will substantially mitigate this problem.

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