Mobilizing Archaeologists

Increasing the Quantity and Quality of Data Collected in the Field with Mobile Technology

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ABSTRACT

Data collection takes up much of the already limited time archaeologists have to excavate and often requires additional time to digitize. Moreover, despite efforts to standardize data, archaeologists often find errors such as blank or incorrectly recorded fields. To avoid these issues, several projects have made use of tablet computers to streamline and digitize data, but this process can be opaque, specialized, and expensive. Previous research has addressed neither the general feasibility of developing and utilizing mobile devices for data collection nor the quality and quantity of these data. In this article, I review existing methods and practices for integrating data collection on mobile devices in order to evaluate the costs and feasibility of transitioning to a mobile-based data collection system. Through a case study using OsteoSurvey, a series of bioarchaeological data collection forms for Android tablets, I assess the efficacy of data collection on mobile devices. An experiment comparing OsteoSurvey to traditional paper forms demonstrates that participants saved time and made fewer mistakes using the OsteoSurvey forms, resulting in the collection of 21–32 percent more data. Consequently, data collection with mobile devices can significantly increase the overall productivity and quality of archaeological research.

La recolección de datos ocupa una gran parte del poco tiempo que los arqueólogos tienen para excavar, y muchas veces es necesario perder aún más tiempo para digitalizar estos datos. Además, a pesar de los esfuerzos para normalizar los datos, los arqueólogos suelen encontrar errores como espacios en blanco o datos incorrectamente registrados. Varios proyectos han integrado computadores personales de forma tablet para evitar estos problemas mediante la racionalización y la digitalización de los datos, pero este proceso puede ser poco claro, especializado y costoso. Investigaciones previas no se han enfocado en la viabilidad del desarrollo y la utilización de dispositivos móviles para la recolección de datos ni la calidad o cantidad de los mismos. En este estudio, se revisan los métodos y las prácticas existentes para la integración de la recopilación de datos en los dispositivos móviles con el fin de evaluar los costos y la viabilidad de la transición a un sistema de recolección de datos en dispositivos móviles. A través de un caso de estudio sobre la OsteoSurvey—una serie de formularios en tablets Android de recolección de datos bioarqueológicos—se evalúa la eficacia de la recolección de datos en dispositivos móviles. Un experimento que compara la OsteoSurvey con los formularios tradicionales en papel demuestra que los participantes se demoraron menos tiempo y cometieron menos errores en la OsteoSurvey que en los formularios en papel, lo que resulta en la recolección de entre el 21 al 32 por ciento más de datos. En consecuencia, la recopilación de datos con los dispositivos móviles puede aumentar significativamente la productividad y la calidad de la investigación arqueológica.

Illegibility, incomplete data sheets, and interobserver error are some of the numerous difficulties archaeologists face when collecting data in the field. Archaeologists often lament the hours spent filling out paperwork, which consumes time we could otherwise spend excavating. Furthermore, the pervasive employment of cryptic data encoding—arbitrary numbers or symbols to represent more complex ideas—as a means to speed up paperwork invariably leads to mistakes when data sheets are digitized and de-encrypted in the lab. Over the past several years, excavations have begun to use mobile devices such as tablets and smart phones to avoid these problems and to automatically digitize data collected in the field. With the decreasing costs and increasing availability of mobile phones and tablets, this trend is likely to continue to grow. However, the development and employment of existing mobile data collection software is not always transparent, nor cost-effective for wider implementation. Further, little testing has been done to demonstrate the efficacy of mobile-based forms over paper forms in archaeology.

Digitizing data is becoming a practical requirement for fieldwork. The National Science Foundation's mandatory data management plan forces archaeologists to demonstrate a strategy for long-term archiving and dissemination of all data created during research. Even before this, archaeologists recognized the imperative for digital infrastructure (Kintigh 2006) and the necessity for long-term data preservation (Ogburn 2010). Most projects, therefore, include a digitization plan for any data recorded on paper in order to offer an accessible, durable, and cost-effective means of storage. In this article, I suggest viable means for projects, regardless of size, to develop their own digitized data collection strategy in order to ensure that their data are "born digital." These data collection methods can then include means for upload to a server for archiving, thus automating the data management process.

I address the development of mobile-based data collection strategies in two ways. First, I review some of the most recent research using mobile devices to summarize existing methods for digital data collection and to explore potential limitations of tablets in fieldwork. Through this review, specialists or small archaeological projects can establish how feasible it is to create and employ their own data collection applications. Second, I evaluate whether collecting data on mobile devices can actually improve the quality and quantity of data collected in archaeological research. I offer the OsteoSurvey application—a series of bioarchaeological data collection forms for mobile devices—as a case study. After demonstrating how OsteoSurvey was developed, I present an experiment comparing it to paper forms in order to determine whether the OsteoSurvey application can act as a higher quality and more efficient data collection solution than traditional paper forms.

PROBLEMS AND PRIORITIES IN DATA COLLECTION

Existing Data Collection Strategies for Mobile Devices

The use of mobile devices for data recording can instantly resolve several types of problems inherent with paper data recording in the field. Digital documentation avoids issues of illegible handwriting, limited space for recording comments, running out of copies in the field, and the need to digitize data after collection. Moreover, mobile devices can enhance data collection in ways previously unimaginable; using one simple device, we can now automatically link data entries with coordinates obtained from the Global Positioning System (GPS) and with photographs and video recordings. We can instantly digitize drawings in the field, and even overlay those drawings on top of photographs taken simultaneously. Despite these advantages, however, concerns about cost, development, and potential new problems make many archaeologists hesitant to employ mobile devices for data collection in their projects. The following review clarifies the methods used to develop digitized data collection forms and addresses potential new issues such as battery life and hardware costs.

Mobile devices have been used for data collection in archaeology since the introduction of handheld PCs (e.g., Spinuzzi 2003). Subsequently, archaeological data collection on mobile devices has evolved to integrate mobile phones and tablets. These now allow for data collection to include the touch interface, web operability, and hardware features of tablets themselves. This process has been most clearly documented in blogs dedicated to this topic by Wallrodt (2014) and Beard (2013).

Projects can use three major approaches to employ digitized data collection: (1) hire a programmer to write a program for data collection; (2) use applications and software to integrate existing databases and forms; and (3) use open-source applications to modify prefabricated data forms or design new ones. Each of these approaches come with comparable advantages and disadvantages in terms of the time, money, and expertise required for developing digital data collection on mobile devices.

The most tailored solution requires the hiring of a programmer to customize data forms to meet project needs. The Pyla-Koutsopetria Archaeological Project (PKAP) built a custom form using HTML5, CSS, and mySQL databases (Fee et al. 2013). This solution is flexible because it is platform agnostic—it can be implemented on mobile devices regardless of operating system. A custom interface could also be manageable on smaller mobile devices such as cell phones. However, the time and cost involved in using a programmer can limit the complexity of data collection software. Additionally, if problems arise in the field, it may be difficult or impossible to quickly resolve the issue. Consequently, while the employment of a programmer for developing custom forms offers the most flexibility in terms of layout and design, it may prove too costly for smaller projects or individual researchers.

A much simpler solution is to use applications and software to link your current database or data entry forms with mobile devices. At Pompeii, archaeologists have used iPads running the application FMTouch to integrate field observations with their FileMaker Pro database (Ellis and Wallrodt 2011). Other projects have also adopted the approach of simply linking iPads to existing databases (Houk 2012). Such projects may require relatively little time to begin using mobile devices for data collection, as the majority of work needed to develop data collection forms is already completed when the database is built. This approach also allows for a quick integration with previous research, since it simply involves adding to an existing project database, thus increasing productivity without necessarily costing additional time or expense. After fully implementing iPads for data collection in the field, the team at Pompeii saw a 371 percent increase in productivity with 35 percent fewer team members (Poehler and Ellis 2012:2).

Unfortunately, this approach has several potential disadvantages. Database layouts must be simultaneously manageable on a mobile device and a computer, limiting the complexity of the forms and requiring a mobile device with a screen large enough to display the data form effectively. Additionally, Houk found that syncing all four of the iPads used for data collection with a master database was time consuming and created unanticipated problems in the field (2012:80). The project's database included a parent-child hierarchy whereby forms had to be nested beneath higher level forms. Consequently, each device needed to have the highest level forms, such as the site summary, even though only one of these could exist in the master database. While these issues are resolvable, such unplanned problems can be time consuming during the initial implementation of mobile devices for data collection.

The E'se'get Archaeology Project utilizes preexisting applications to modify PDF documents, making it easy to create data collection forms on Adobe Acrobat Pro and then to record data on any mobile device (Bett 2012a). This solution allows for simple data presentation, is platform agnostic, and requires little to no programming experience for its setup and execution. This simple design, however, prevents more complex data entry protocol such as skip logic, data validation, and linking with GPS and camera capabilities, thus limiting data collection to functions that already exist in paper forms. Still, data from these forms can be exported independently, which enables efficient integration into a database.

These projects all utilize additional applications to expand how they collect data in the field. Researchers use iDraw (Ellis and Wallrodt 2011) to create scaled drawings more quickly and efficiently than on paper. This application allows users to draw with a stylus on a grid, mimicking current approaches using a pen and graph paper. Users can copy layers from a previous drawing, automating much of the work in daily top-plans. Finally, projects can overlay drawings on a photograph to create annotated photographs quickly and accurately.

The final approach to developing digitized data collection is to use open-source software to modify existing data collection forms or even create new ones molded to a project's needs. This requires relatively simple programming, as the majority of such platforms utilize eXtensible Markup Language (XML). XML allows users to define their own elements, thus extending the terms recognized as meaningful to both computers and humans. For example, using simple start- and end-tags, a user can markup an artifact's location:

```
<Stratigraphic Unit>110</Stratigraphic Unit>
<Site>Deir el-Medina</Site>
<Region>Luxor</Region>
<Country>Egypt</Country>
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XML allows archaeologists to define an infinite number of fields, and attributes assigned to these fields can delimit the kinds of information recorded. Moreover, the simple parsing of XML documents enables them to be independent of software or language, while also being more ideal for archiving (Ross et al. 2004:61–64). Many archaeologists (e.g., Falkingham 2005; Schloen 2001; Snow et al. 2006) have already embraced and advocated for XML, as it is both flexible and conducive to structuring data for long-term storage and the dissemination of gray literature.

Open data kit (ODK), Epicollect, and Cybertracker are three open-source applications which allow archaeologists to develop custom XML-based forms and are often implemented in developing countries for epidemiological (e.g., Rajput et al. 2012), ecological (e.g., Ansell and Koenig 2011), and geological research (e.g., Djuric 2013). The process of developing these forms is aided by online simple design tools to circumvent the need to write in XML. While the process of developing forms may be time consuming prior to fieldwork, these forms allow users to integrate data validation, skip logic, GPS coordinates, and multimedia into data collection. These forms can be modified in the field and do not require extensive programming experience. However, as there is no guarantee that these open-source applications will be maintained, archaeologists risk software obsolescence. As a result, these open-source software options may not be suitable for longer-term projects.

Archaeologists are offering an increasing number of open-source software options designed specifically for archaeological data. The Integrated Archaeological Database (IADB) was originally intended to facilitate digital publication of archaeological data, but now includes a mobile-based data collection component (Rains 2011). Alternatively, OpenDig, developed by Matthew Vincent, is designed specifically for iOS devices such as iPhones or iPads (Levy et al. 2012:12). It allows customized data structuring for loci recording, but also includes a set of preexisting data structures to allow immediate integration into projects with non-specific data recording methods. It was used at Tall al-'Umayri with an integrated online database available for public access (Madaba Plains Project 2009).

OpenDig is being integrated with Archfield to create a more complete archaeological data collection system for mobile devices. Archfield is an "open-source, real-time, 3D recording system developed as a solution to archaeologists' digital field recording needs" (Levy et al. 2012:11). It includes wireless integration with total stations to allow accurate coordinates to be recorded within a data entry for an artifact. This can then integrate with label generators to create unique barcodes for artifacts that can link to the artifact's data entry. It is platform agnostic and designed to facilitate easy online archiving (Smith and Levy 2012).

Finally, the Federated Archaeological Information Management Systems Project (FAIMS) has most recently released an Android-based application specifically designed for archaeological data collection (Sobotkova and Ballsun-Stanton 2013). This is the most publically accessible option for archaeologists. Functionality for this mobile application supports skip logic—the conditional branching of survey questions based on previous answers—as well as data validation to ensure that data are properly entered. The FAIMS mobile application, therefore, allows for relatively complex data collection forms.

Overall, these open-source software options for archaeological research may be the most fruitful and time-efficient option for projects to integrate mobile devices into data collection. One should remember, though, that many of these are still in development, and customizing these forms for one's own project may require additional programming.

The Cost and Durability of Hardware in the Field

Another primary concern with the use of mobile devices is the expense of purchasing tablets or smart phones for a project. For projects with a high volume of forms, however, the compounded expenses of paper copying and data entry make paper-based data entry more expensive than tablets (Davis et al. 2012: 290). Additionally, the cost of tablets is becoming even less prohibitive as more brands compete on the world market, and the ubiquity of smart phones could allow researchers to use their own personal devices for data collection.

Another potential limitation is the battery life of tablets in the field. Most missions reported that this did not actually inhibit research. For example, in Fort Vancouver, researchers found that tablets used only 20-40 percent of battery power for a full day's use (Wilson 2013). Similarly, PKAP found that battery life was more than sufficient after a full day's research, and neither dust nor heat negatively impacted tablet operation (Fee et al. 2013: 54). While glare when recording in direct sunlight is another serious issue, most found ways around this problem by taking advantage of shade or anti-glare covers (e.g., Pettegrew 2012). Finally, waterproof, touch-sensitive cases have been developed for tablets, and these have been demonstrated to offer sufficient and effective protection for iPads during light rain, when paper data recording was otherwise impossible (Houk 2012:74).

A CASE STUDY IN DEVELOPING, IMPLEMENTING, AND ASSESSING DATA COLLECTION ON MOBILE DEVICES

While the current methods and costs show that data collection on mobile devices is a viable option for a variety of projects, previous archaeological research has not yet established whether mobile devices offer a more effective means of data collection than paper forms. In medicine, research comparing digital and paper forms has been conducted to assess the impact of digitizing health records at hospitals. Systematic reviews of research comparing digital and paper data collection at hospitals have demonstrated that computer terminals and touch screens are usually more cost-effective, faster, more reliable, and preferred by most users (Dale and Hagen 2007; Häyrinen et al. 2008; Poissant et al. 2005). Yet these studies usually do not explicate the specific methods used in developing digital forms to improve the quality and efficiency of data. The types of data recorded in these studies are also undefined, making it difficult to assess how digital forms collected in hospital environments compare to the types of information recorded in archaeological research. Consequently, the following case study using OsteoSurvey explores how the development and employment of mobile-based data collection can improve both the quality and quantity of data collected in bioarchaeological research. It describes the methods used to improve data collection, while also testing the quality of data from digitized forms against paper forms.

I developed and employed the OsteoSurvey application (Figure 1) during osteological fieldwork at Deir el-Medina, Egypt, during the 2012 and 2013 field seasons. This UNESCO World Heritage Site (Figure 2) contains the village and cemetery of the workmen who built the royal tombs during Egypt's New Kingdom period (1550–1080 B.C.). The extent of the remains present, the lack of sufficient off-site storage, and the current political climate in Egypt necessitated the development of OsteoSurvey so that data collection could be employed inside the tombs, while also inventorying the remains in their commingled state.

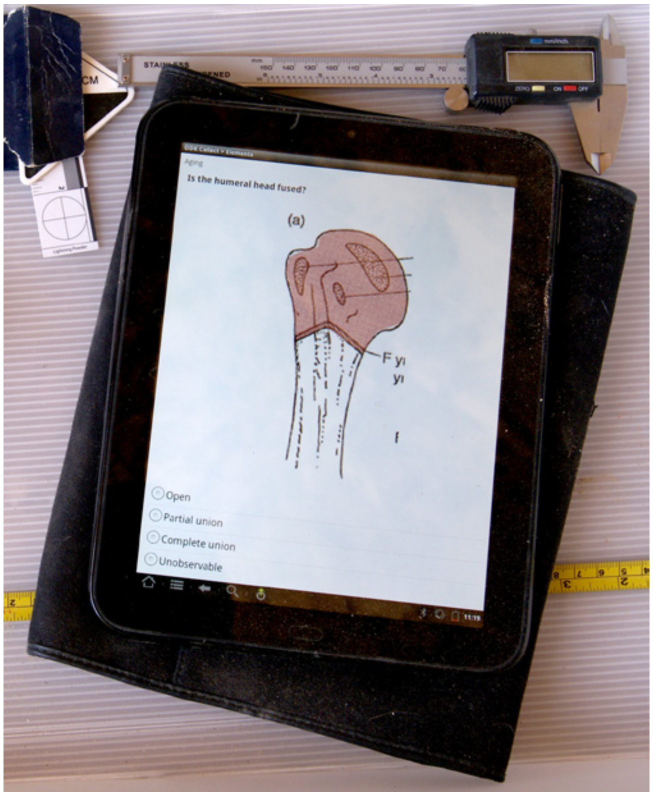

FIGURE 1. OsteoSurvey in use on a Hewlett-Packard Touchpad tablet during fieldwork at Deir el-Medina, Egypt.

OsteoSurvey is an ideal case study, as it offers bioarchaeological observations mimicking the kinds of data traditionally recorded on paper forms in the field, thus offering a direct comparison of the data. This includes the same techniques and observations found in Buikstra and Ubelaker (1994) for inventorying remains, assessing the age and sex of individuals, and detailing metric and non-metric observations for assessing pathologies, hereditary traits, and taphonomy.

Developing the OsteoSurvey

There were four primary aims in developing the OsteoSurvey application. First, it was necessary for OsteoSurvey forms to allow users to record the same values and follow the same methods as those outlined in Buikstra and Ubelaker (1994). This is the standard volume for osteological data collection and offers a series of comparable paper forms to be used while observing human remains. Second, it was necessary to be able to record data for complete individuals as well as for individual elements. At many archaeological sites, human remains are found com-

FIGURE 2. The excavated village of Deir el-Medina, Egypt, and surrounding tombs.

mingled and disarticulated since burial, making it necessary to catalog individual elements if they cannot be rearticulated with the rest of an individual. Third, OsteoSurvey had to be able to support skip logic, which allows the form to automatically skip fields based on previously recorded data. For example, if the left femur of an individual is missing or incomplete, the form could automatically skip the step of asking the user to record its length. Finally, it was fundamental that OsteoSurvey support embedded media files, as some of the methods employed in Buikstra and Ubelaker require visual comparison with a sample image (e.g., methods for observing non-metric sex characteristics of the skull).

Given the need for complex forms and the limited budget of the project, I chose to design the OsteoSurvey application using a preexisting open-source data collection platform for mobile devices. To determine the best platform for developing OsteoSurvey, I compared key features for several different open-source options that could be operated on an Android tablet. Ultimately, Open Data Kit (ODK) offered the most robust tools for developing longer and more complex forms, and it was specifically designed to accommodate the challenges of working in remote areas or developing countries (Brunette et al. 2013; Hartung et al. 2010). ODK supports more than a dozen question types, including the incorporation of multimedia and data entry restrictions (e.g., an integer between zero and five). Most importantly, ODK allows users to utilize skip logic to supply only applicable data fields. One of the biggest advantages of ODK is its extensive development and documentation, as well as its support of other Google services; data can be instantly evaluated through Fusion Tables and can even be secured through one's own private server for free. Moreover, accompanying tools are designed to facilitate the development of complex forms without encoding in XML through the use of spreadsheets and online form designers. Finally, data can be exported into a universal comma-separated value (CSV) file without requiring an internet connection, another key concern for utilizing OsteoSurvey, given that internet connectivity in the field is often limited or unavailable.

OsteoSurvey consists of separate forms for recording the skull, dentition, individual elements, and complete individuals. These forms were specifically designed to reduce errors during data collection. Data collection errors can be grouped into random, systematic, and illegitimate errors (Gnaden and Holdaway 2000). Random errors account for variation in observations such as subjective differences in the identification of a soil type or small metric differences in the measurement of a humerus. These usually do not significantly alter the data collected, as the variation is small and distributed randomly. Systematic errors, on the other hand, imply a consistent misapplication of methods for observation, such as measuring a humerus from the wrong landmarks or always writing the wrong code for an observation. These systematic errors skew the evidence in the same direction, leading to misinterpretations of the archaeological evidence. Illegitimate errors are mistakes made during data collection, such as missing an observation or accidentally transcribing a measurement incorrectly. While these are randomly distributed, they can deeply impact the interpretation of data. Entering the maximum length of an artifact as 11 mm instead of 110 mm, for example, could introduce an extreme outlier into a data set. While random errors are often unavoidable, they have a relatively low impact on the data set. On the other hand, illegitimate errors have an intermediate impact on the data set through the introduction of outliers, but they can be partially avoided. Finally, though systematic errors can have the greatest impact on the data, they are entirely avoidable through consistent and clear data collection strategies.

Atici et al. (2013) analyzed an orphaned zooarchaeological data set to demonstrate how these errors can deeply impact the integrity of project data. In order to make a legacy data set suitable for digital analysis, the researchers had to systematically rename fields (e.g., ensure that all taxa are named by their Latin genus name), remove data that had information clearly entered into the wrong field, and ignore anything with insufficient metadata. As a result, they had to exclude 44 percent of the data set, reducing it from 30,000 to fewer than 17,000 elements (see Atici et al. 2010 for the cleaned data set of only 16,824 elements). Furthermore, prior to their analysis, the original data set had been transferred to punch cards and eventually digitized in spreadsheets. This process not only increased the potential for errors in transcription, but also cost a great deal of time and money for digitizing, archiving, and preparing the data set. In this example, inefficiencies in data collection and archiving cut in half the amount of information available to researchers and consumed more resources for curation than was likely originally spent on collection.

There were several ways OsteoSurvey was designed to limit systematic and illegitimate errors during data collection. The number of observations recorded per screen was often limited to only one observation. This helped to ensure that recorders did not accidentally miss or skip required fields. Each screen could then contain all of the necessary information for the field, such as definitions of terms and methods. When the data being collected were from a limited set of predefined values, the forms were designed to allow the user to directly select the appropriate value. For example, when making observations on the supra-orbital ridge, the form allows the user to select the most appropriate image, rather than record a scalar number to represent that image (Figure 3). The form then automatically records the observation as the appropriate number, eliminating illegitimate and systematic errors due to incorrect transcription. The forms were also designed to automatically record data already available on the mobile device, such as the date and time, thereby saving time during data collection and avoiding additional illegitimate user errors.

Assessing the Qualitative and Quantitative Advantages of OsteoSurvey Forms

To assess the efficacy of OsteoSurvey, I conducted a comparison study with traditional paper forms using observations on the skull. A group of eight volunteer undergraduate and graduate students at UCLA who had taken at least one introductory osteology course observed four skulls with both paper forms and Android-devices (Figure 4), resulting in a total of 64 data sets with 32 paper and 32 digital forms. I measured the amount of time per entry, number of improperly entered or missing fields, and the interobserver variability in cranial metrics. The four skulls used in this study were from the teaching collection available in the Anthropology Department at UCLA. Three of the skulls were complete, allowing for full metric and non-metric observation. One was only partially complete, thus appropriate for testing the efficacy of skip logic for reducing the time spent recording unobservable measurements.

The participants were asked to record (1) an inventory of elements present on the skull and (2) the sex, age, cranial non-metrics, and cranial metrics, as outlined in Buikstra and Ubelaker (1994). Before any data collection took place, participants were given a brief tutorial on how to observe and score for each of these methods. Participants recorded the start time and end time for their observations for each skull. Half of the group began with the paper forms and then switched to the OsteoSurvey forms; the other half, conversely, began with OsteoSurvey forms and then switched to paper forms. Participants were provided with the same brand and model of spreading and sliding calipers. Participants were allowed access to Buikstra and Ubelaker (1994) while recording on paper, but not while using the tablet.

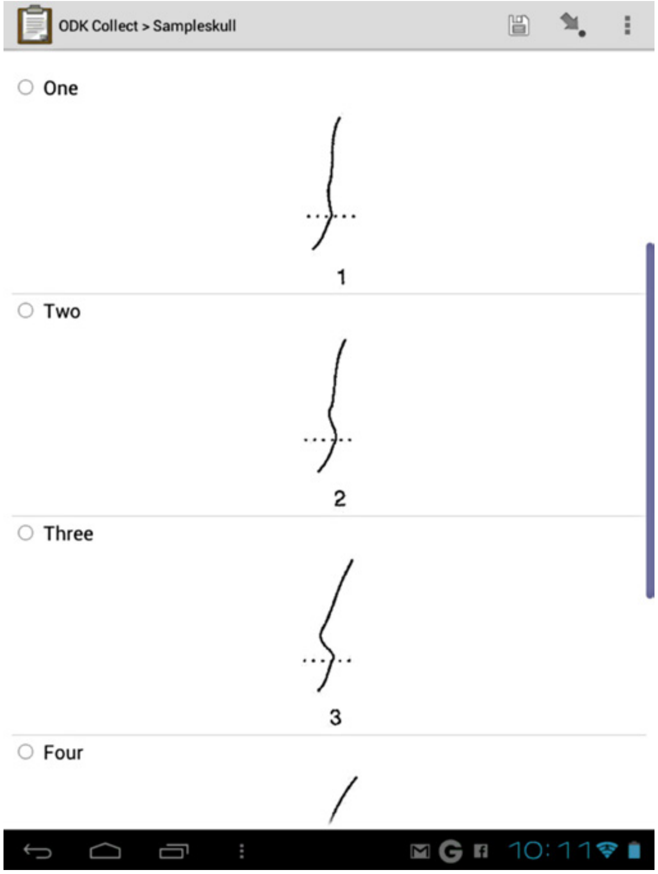

FIGURE 3. Scoring the supra-orbital ridge with OsteoSurvey by selecting the most appropriate image, rather than recording an ordinal value.

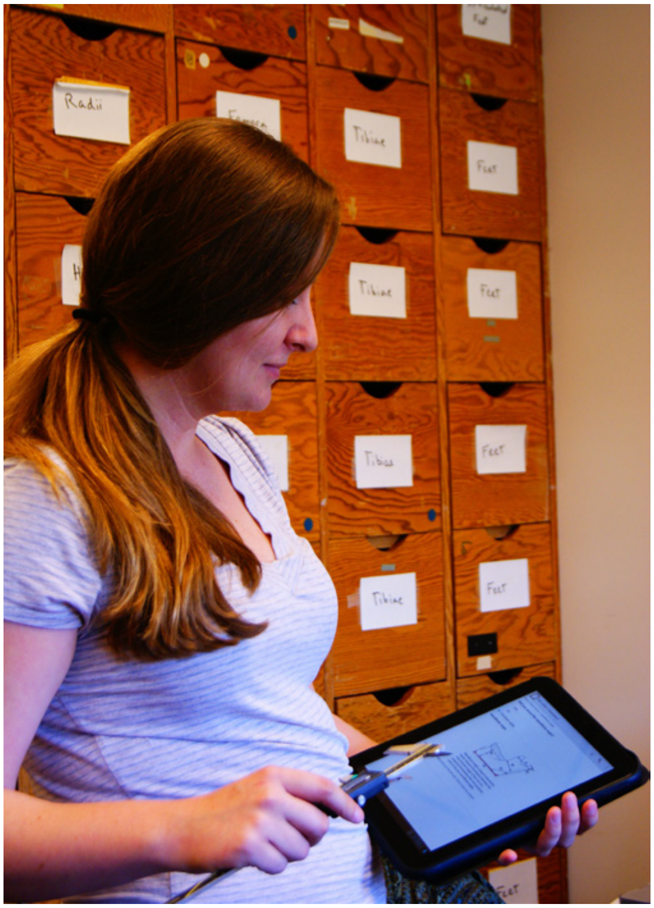

FIGURE 4. Participant Brittany Jackson using OsteoSurvey in the comparison study.

After participants completed their observations, I evaluated the paper and digital forms for both systematic and illegitimate errors by counting the number of improperly recorded fields. Specifically, I counted an improperly recorded field if it was left blank, measured in the wrong scale (e.g., centimeters rather than millimeters), or used the wrong scoring scheme (e.g., "unobservable" instead of "9"). This method does not include random errors, nor does it consider other potential systematic and illegitimate errors more difficult to observe, such as reading the calipers improperly.

I also compared measurements of the skull to determine whether the mobile forms ensured more accurate metrics. I assessed these metrics by comparing outliers produced using the paper and digital forms, assuming that a higher number of outliers would represent a greater number of illegitimate and systematic errors in the participants' metric observations. An assessment of outliers ignores the expected variation in data due to random error by prioritizing only those data points outside of a normal distribution. These data are graphed as the distances from the median per cranial metric. Such visualization instantly separates the differences due to random error (i.e., smaller variation near the median) from those likely due to illegitimate or systematic errors (i.e., outliers).

The time spent recording was averaged and then compared using a two-sample one-tailed *t*-test in conjunction with a two-sample *F*-test to determine equal or unequal variances. The total counts of missing and improperly recorded fields were compared using Fisher's exact tests and chi-squared tests. Fisher's exact tests were used when sample sizes were insufficient for a chi-squared test because the Fisher's exact test, as the name implies, offers exact *p*-values even with small samples. An alpha level of .05 was used for all tests.

Results

Figure 5 shows the distribution of total time required per skull for the OsteoSurvey forms, as compared to paper forms. In general, participants required less recording time with the OsteoSurvey forms and there was less variation in the maximum and minimum duration required. Participants saved, on average, nearly six minutes per entry while using the tablet ($\mu = 36.3$, $\sigma = 6.72$) over paper forms ($\mu = 42.2$, $\sigma = 7.9$). This difference is statistically significant in a one-tailed *t*-test (*t*[61] = 3.24, *p* = .001). A post-hoc power analysis of this *t*-test using G*Power 3.1.7 (Faul et al. 2007) showed that the effect size was large enough to give the *t*-test 93 percent power. Given the time saved, mobile-based data recording could increase the total amount of data recorded in the field by as much as 16 percent. This does not even take into consideration the additional time saved by eliminating the need to transcribe data from paper forms into a project database. The amount of time saved is likely due, in part, to the application of skip logic, which automatically reduces the number of possible observations based on elements present. Additionally, the automatic progression of the survey to the next observation may have kept participants more focused, increasing their productivity.

Participants also made significantly fewer transcription errors and skipped fewer fields while using the tablet. Of 32 paper forms, 25 had at least one incorrect scoring transcription. For example, in one form, a student wrote "indeterminate" for the estimated sex, rather than a value between zero and five. While this could be corrected later during analysis and digitization, if left as is, the data might not be automatically counted when summing the number of individuals who were male, female, and indeterminate. Within OsteoSurvey, transcription errors are mostly eradicated, as the program records the underlying value for you. Only four fields were transcribed incorrectly in the

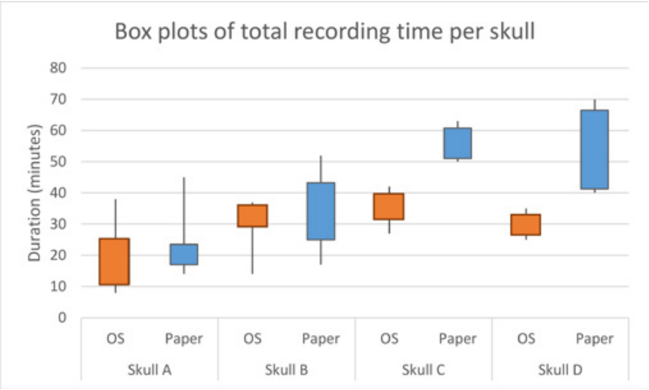

FIGURE 5. Total recording time for OsteoSurvey forms vs. paper forms.

TABLE 1. Contingency Table of Transcription Errors

	Transcription Errors		
Survey type	**Present**	**Absent**	**Total**
Paper forms	25	7	32
OsteoSurvey	4	28	32
Total	29	35	64

TABLE 2. Contingency Table of Missing Fields

	Missing Fields		
Survey type	**Total Empty**	**Total Recorded**	**Total**
Paper forms	250	3888	4138
OsteoSurvey	54	4084	4138
Total	304	7972	8276

32 OsteoSurvey forms. The Fisher's exact test for the distribution of transcription errors (Table 1) was highly significant ($p < .001$). Additionally, these four errors in the OsteoSurvey forms were all illegitimate, having occurred at random, consequently reducing the total number of erroneous fields due to the lack of systematic mistakes. Systematic transcription errors on paper forms potentially involve encoding dozens of fields incorrectly. For example, one participant did not use the numeric scoring system for the inventory to differentiate between complete, incomplete, and partially complete elements. Instead, the participant simply marked whether an element was absent or present. This systematic error not only resulted in 16 transcription errors, but also led to the loss of valuable information on the relative completeness of each of these elements. Consequently, while some systematic transcription errors can be corrected during data analysis, others will cause data losses; in this case, the paper form's inaccurate inventory, 11 percent of the total fields in the form, significantly reduced the value and completeness of the entry.

The contingency table for accidentally missing fields (Table 2) also shows that the tablet had significantly fewer blank fields than the paper forms, x^2 (1, $N = 7972$) = 131.1, $p < .001$; this is also due to the relative lack of systematic errors. The mean number of empty fields per paper form was 7.8, while in OsteoSurvey, it was only 1.7. The majority of these empty fields were unobservable due to an incomplete skull, so it was logical that participants did not enter any information. In these cases, however, the methods ask that the observer record a "9" to indicate that the field is unobservable. When later reevaluating these data, it would be impossible to know whether the fields were left blank because they could not be observed or because they were observable but skipped. The total missing fields for the paper forms represented six percent of the total fields in the forms, whereas for OsteoSurvey, it represented only one percent. This difference means a five percent loss in the total data collected due to using paper forms rather than OsteoSurvey.

Finally, paper forms also had slightly more outliers in cranial metrics than the OsteoSurvey forms. Among cranial metrics observed on the three complete skulls, there was a total of nine outliers in the paper forms and only four in OsteoSurvey. Figure 6 shows the distribution of participants' measurements of skull B, based on the distance from the median per cranial metric. While the distributions of the data from the paper forms and OsteoSurvey show relatively similar variance in general, the paper forms generated several more outliers than the OsteoSurvey forms. This suggests a slight advantage for utilizing OsteoSurvey in reducing interobserver variation, though the results are generally neutral and would benefit from a larger sample size for sufficient testing.

One reason to explain lower variance in data from OsteoSurvey is its display of the detailed description and diagram of the landmarks for each measurement. While the paper forms show all of these descriptions and measurements on the same page, OsteoSurvey separates each measurement, offering only the applicable description and image simultaneously. This may prevent confusion when determining how to conduct each measurement.

Such a mistake is exemplified in the paper forms. One observer recorded two outliers successively: 23 mm for the nasal height and 38 mm for the nasal breadth. These cranial metrics had medians of 41 and 24 mm respectively. It is interesting to note that this observer's measurements fit within one standard deviation of the median for the next two measurements— the nasal breadth and orbital breadth. It is possible that the observer accidentally skipped the nasal height, recording the nasal breadth in its place. If this was the case, these two outliers could have been avoided if the measurements were on separate forms.

At the same time, OsteoSurvey may not have reduced the number of systematic errors when recording cranial metrics. Similar outliers for the interorbital breadth and mastoid length were recorded by the same participant, suggesting that this individual was measuring incorrectly regardless of form type.

Discussion

These data suggest that use of OsteoSurvey in fieldwork could result in a marked increase in the osteological data available to researchers for analysis. The combined loss of data from missing fields (5 percent), time spent filling out the survey (16 percent), and transcription errors (11 percent) accounted for 21–32 percent more data lost using the paper forms. This statistic does not include qualitative differences in the data, as exemplified by fewer outliers in the cranial metrics collected with OsteoSurvey. These results demonstrate the efficacy of utilizing mobile devices for data collection in place of paper forms to prevent simple errors from obstructing data collection and reducing both the quantity and quality of data collected in the field.

This research was specifically conducted with entry-level students and thus may reflect a higher number of transcription errors and variation than one would achieve with more advanced researchers. However, this reflects the reality of data collection with field school participants, making mobile devices extremely beneficial for data collection during large field school projects.

As this study aimed to directly compare paper forms with OsteoSurvey, it did not take into consideration additional features in

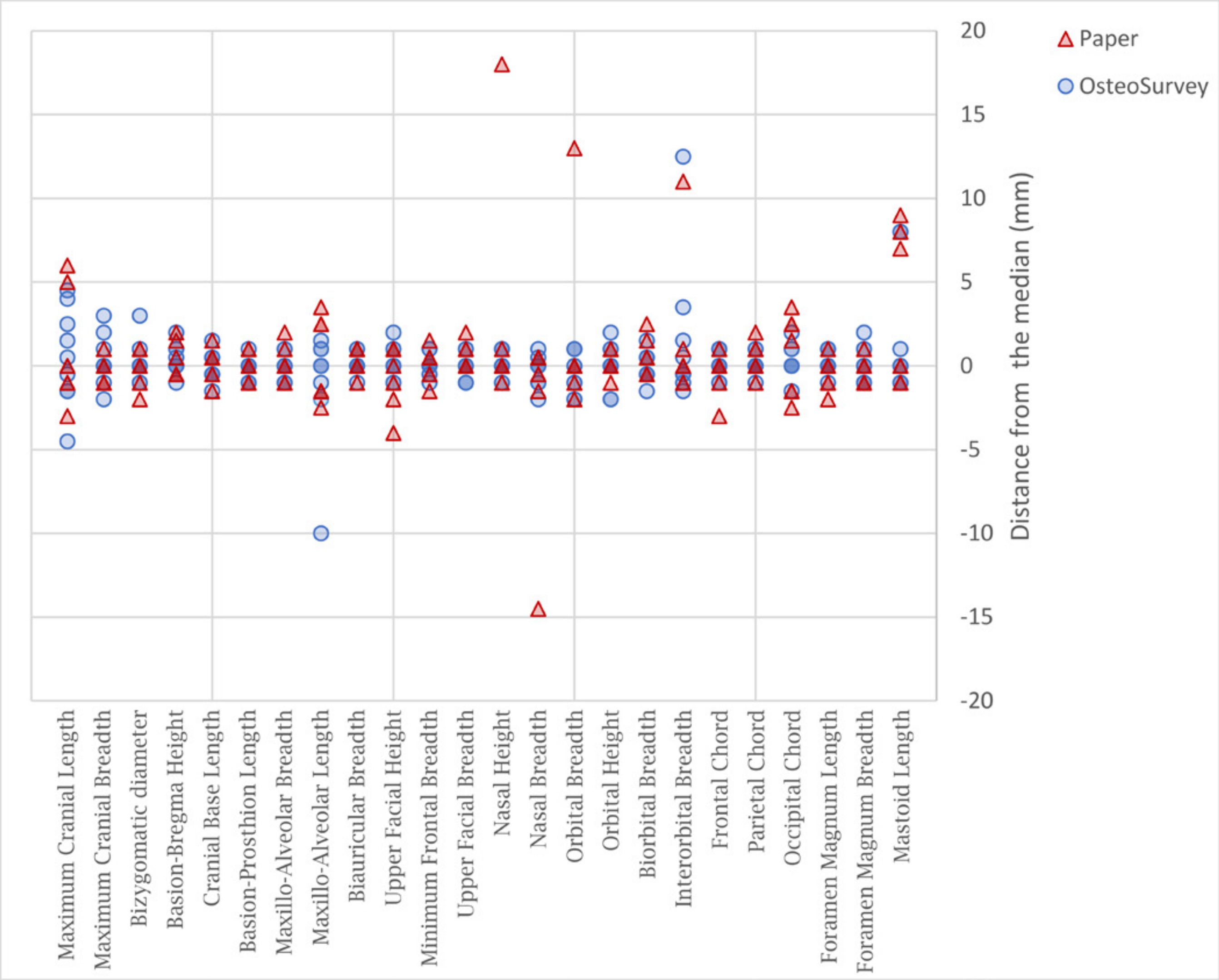

FIGURE 6. Graph of the distance from the median for cranial metrics of Skull B.

mobile devices that make them especially useful during data collection. Audio and video recordings can be taken for each form to capture either lengthy descriptions or three-dimensional views, respectively. Photos can also be taken to reference an artifact later during analysis. Finally, mobile devices can automatically record GPS coordinates, device IDs, and timestamps when a form is filled out, thus reducing the time spent on data recording and automatically connecting these data with the same entry. These hardware advantages make data collection with mobile devices particularly well suited to archaeological surveys. Mobile devices can also access online databases, bringing new resources directly into the field to improve the quality of data collected. For example, the E'se'get Archaeology Project (Bett 2012b) references Virtual Zooarchaeology of the Arctic Project (VZAP), a 2D and 3D online vertebrate reference collection, to assist with identifying faunal material in middens.

This research does not address potential issues that might arise in analyzing data after its collection. While data were recorded within the context of metadata, such as images and instructions to describe what the observer is measuring, these data are decontextualized in the exported CSV files. These files also include all observations for one data entry in a single line, resulting in potentially long and indiscernible series of data fields. While this design is easier for quantifying data on a large scale, CSV files are less manageable for quickly looking up and comprehending individual measurements. Databases can easily import CSV files to structure and contextualize data. However, creating and linking database information with CSV exports requires additional time and resources. Future research should evaluate best practices for documenting and archiving metadata for data born in CSV files, especially as more projects integrate more diverse data. Additional research should further evaluate data curation as more projects integrate digital data collection strategies. Projects and specialists should determine whether they require large-scale quantification for their data sets. If they do not, data collection on tablets via PDF or preexisting databases may be a more ideal strategy for mobile devices than developing data collection forms that export data as CSV files.

CONCLUSION

Ever since handheld PCs were first introduced, archaeologists have been using mobile devices for collecting data. This article explored the methods archaeologists currently use to develop forms for data collection on these mobile devices. Projects can hire programmers to develop custom forms, utilize applications to convert their databases for use on mobile devices, or employ preexisting open-source platforms to create and display their own customized XML-forms.

In an experiment to compare data collected with OsteoSurvey forms against similar data collected on paper forms from Buikstra and Ubelaker (1994), the digital interface offered faster data collection and more consistent observations. Skip logic and data validation likely contributed to participants' ability to record data faster and with fewer systematic errors using OsteoSurvey. Overall, the use of OsteoSurvey resulted in a 21–32 percent increase in the amount of useable data collected when compared to paper forms. In the field, this could equate to an almost one-third increase in the total number of human remains recorded.

These results demonstrate that mobile devices offer a new platform for archaeologists to collect data faster and more reliably. Recent developments in open-source solutions for data collection have made the development of mobile forms inexpensive and user-friendly. They can be cost-effective for larger projects and offer the greatest benefits to archaeological projects involving field schools or survey work. As more projects adopt "digitally born" data collection solutions, additional research should address the best means for analyzing, publishing, and archiving these data sets to make them comprehensive and lasting legacy data.

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Data Availability Statement

Forms for OsteoSurvey used during testing, as well as survey results from testing, are publically available online at http://bioarchdata.appspot.com. Skulls used for this study are currently stored in the UCLA osteological collection under the numbers 1908 (skull A), X78 (skull B), 25538 (skull C), and 25539 (skull D). Requests for access to these skulls can be made to the UCLA Department of Anthropology (375 Portola Plaza, 341 Haines Hall, Box 951553, Los Angeles, CA 90095-1553, USA; telephone +1 310-825-2055).

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