Pilot Assessment of Physiological Measures for Construction Workers

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Limited data exist informing how and to what extent construction activities impact worker health and productivity. This research explores the impact of construction activities and environmental factors on the health and productivity of five professional construction workers over a two week period as they worked to construct the concrete foundation of the Olympic Museum in Colorado Springs, Colorado, August 2017. The study collects and analyzes physiological data from the construction employees using off-the-shelf monitoring devices. Vital signs and physical indicators measured include factors related to cardiovascular stress, musculoskeletal stress, heart rate, breathing rate and core temperature. The research documents data collection and analysis methods as well as preliminary findings. Findings begin to show how such data can be used to characterize and distinguish health and productivity measures for individual construction workers, across weather conditions and construction activities. The contribution is a demonstration of monitoring and analysis techniques applicable for professional construction workers when performing activities including: leveling dirt, setting walls forms, installing embeds for concrete and driving heavy equipment.

Key Words: Construction Productivity, Physiological Data, Health Metrics, Performance

Introduction

Working on construction sites involves risk, can be physically demanding, and is significantly impacted by environmental conditions. Many construction activities involve heavy lifting, awkward work postures, vibrations, pushing and pulling, and forceful exertions (Hartmann & Fleischer, 2005). Some of these activities can cause immediate injuries, but most of these activities may adversely affect a worker over time. In addition to physical health, physically demanding work can also alter the mental state, which may lead to decreased productivity, poor judgement, inattentiveness, poor work quality, job dissatisfaction, and ultimately more accidents and injuries (Abdelhamid & Everett, 2002). A construction work environment is generally more hazardous than most other work environments due to the use of heavy equipment, dangerous tools, and hazardous materials, all of which increase the potential for accidents and injuries (Abudayyeh et al. 2006). Furthermore, construction work is dynamic, temporary, and "ever evolving" (Brunette 2005). Finally, construction work is often conducted outside in open spaces, where workers are susceptible to temperature-related injuries. Of concern, data from OSHA has stated that heat exhaustion contributes to approximately 30 deaths every year in the construction industry and also significantly impacts worker productivity (Williams, 2013). Significantly, Yi and Chan found that age, alcohol drinking habit, percentage of max heart rate, work duration, and Wet Globe Bulb Temperature are common predictions of labor productivity in construction (Yi & Chan, 2017). In general, researchers have recommended that taking frequent breaks and staying hydrated will reduce heat-related injuries and increase productivity on the jobsite.

Due to a lack of definitive metric to promote optimum conditions, much research is now focused on the use of physiological monitoring devices to get a better indication of construction worker health and productivity. Previous studies have shown that measuring heart rate can be used to determine physiological strain in applied field situations (Kirk & Sullman, 2001). Heart rate, in turn, directly impacts the number of breaths taken per minute. However, breathing rate, on its own cannot, be directly converted to energy expenditure (Gatti, Migliaccio, Bogus, & Schneider, 2014). Physical characteristics such as age, height, weight, and body mass index also influence the amount of physical strain put on a certain individual compared to a peer. Experience and culture may also influence energy expenditure and performance. Hydration can also influence how the body responds during physical activity.

Researchers found that progressive dehydration caused heart rate, core temperature, and perceived exertion ratings to continually increase over time (Murray, 2007). As it is also necessary to assess the physical environment where the work is being performed, researchers have recorded factors such as dry bulb temperature, wet bulb temperature, wind speed, and radiant heat on the construction site (Bates & Schneider, 2008). Researchers have also applied risk management strategies to mitigate the number of accidents related to high temperature working environments (Rowlinson, Jia, Li, & Ju, 2014). Other studies have created early warning systems against heat stress based on environmental and physiological monitoring data (Yi, Chan, Wang, & Wang, 2016).

Recent studies have begun, to a limited extent, to measure physiological data, individual characteristics/experiences, and the role of physical environment on construction worker health. Evaluating the physical demand involved in construction activities requires sensors that can monitor vital signs throughout the workday under active and variable conditions. Since physical demands fluctuate, there is a need for continuous physical measurement so that the significant data can be captured (Hwang & Lee, 2017). For this research, an off-the-shelf system, Zypher's Bioharness is used to monitor construction worker physiological metrics and location data. Zypher's Bioharness system is a tool capable of monitoring construction workers' physiological factors in both real-time and in aggregate. Zypher's Bioharness system has been used successfully to collect data from professional athletes, special forces, rescue workers, and in other research studies. Notably, during the 2010 Copiapó mining accident, 33 Chilean miners wore Zephyr Bioharness devices to monitor their physical conditions (Romagnol, 2010).

Previous research has begun to identify factors that may be useful in assessing physical stress for construction activities under a range of environmental conditions. To date, however, researchers have struggled to identify and validate a convenient and reliable method to collect or combine a set of factors into a functional model, and possible predictor, of construction worker health and productivity. This research tests a method to collect and evaluate workers' physiological data through a pilot application. Researchers monitored five construction workers performing routine construction activities during the summer 2017 in Colorado Springs, Colorado. Previously, the authors piloted this systems on students performing similar construction activities (Clevenger et al., 2018).

Methodology

Five construction laborers working at the U.S. Olympic Museum in Colorado Springs, Colorado were recruited as volunteers for the study. Participation required participants to wear a Bioharness strap and puck under their work clothes while performing construction activities during the duration of the study. Data was collected and uploaded to OmniSense software for analysis. International Review Board protocols for research involving human subjects were completed prior to the research. All volunteers were aware that they could discontinue participation at any time throughout the study. All participations fully participated in data collection for the study's duration, with the exception of one laborer (Volunteer E) who stopped working for the general contractor on day five of the study. Table 1 shows age and physical characteristics of the participants. Zephyr documentation recommends, and researchers elected to enter individual characteristic data into the OmniSense software to better configure physiological status limits (Zephyr Technology, 2016). Volunteers provided their personal data, but not their Body Mass Index (BMI), which the researchers calculated using an on-line calculator based on height and weight. Researchers assigned a BMI category according to the definitions provided by the National Institutes of Health (NIH) (BMIcalc n.d.).

Table 1: Volunteer Information

Volunteer	Gender	Age (yrs)	Height (ft, in)	Weight (lbs)	BMI	BMI Categories:
	M	26	5'9"	215	31.8	Obese
B	M	63	6'2"	219	28.1	Overweight
C	M	52	5'8"	172	26.2	Overweight
D	M	46	6'1"	182	24.0	Normal weight
E	M	40	5'10"	160	23.0	Normal weight

According to NIH, BMI is an estimate of body fat and is a good gauge of an individual's risk for diseases related to body fat. For this research, BMI index is proposed as a proxy for general health and fitness. OmniSense software has an input for fitness level of individual. For this research all volunteers were assigned a three out of ten for fitness for data analysis purposes, although further calibration is recommended in future research.

Eight days of data were analyzed for this study while the volunteers were performing four distinct activities. These activities are defined in Table 2 and include: Setting wall forms, Operating heavy equipment, Leveling dirt, and Installing embeds. Figure 1 is a photograph of the volunteers working on-site during data collection by way of illustration of the activities being performed. In general, all characterization of work activities were based on individual worker entries in their "Pre-task Planning Logs." The pre-task planning log is a safety measure required by the employing general contractor, to be filled out daily by each worker in order to identify upcoming daily activities with the goal to foresee any potential risks or hazards associated with upcoming activities.

Table 2: Timetable of Weather Conditions and Construction Activity by Volunteer

Date	**8/1/17**	**8/2/17**	**8/3/17**	**8/4/17**	**8/7/17**	**8/8/17**	**8/9/17**	**8/10/17**
Climate Conditions								
Temperature (°F)	71	70	64	66	59	63	65	65
Relative Humidity (%)	49	48	70	67	84	77	68	70
Construction Activity								
Setting Wall Forms – Volunteers placed wall forms prior to concrete pours. This usually involved lifting heavy forms and securing them in place.	C, D, E	B, C, D, E	B, C, D, E		C	C	B, C	B, C
Operating Heavy Equipment – Volunteer A was the designated heavy equipment operator onsite, and he was mostly using an excavator during this testing period.	A	A	A	A	A	A	A	A
Leveling Dirt – Volunteers were required to level dirt to the appropriate height. This usually involved heavy lifting.					D	D	D	D
Installing Embeds – Volunteers installed embeds onto the formwork, which required them to climb wall forms to secure embeds while being tied in with a harness.				C, D, E				

Figure 1: Volunteers setting wall forms on-site

BioHarness System Components

The following off-the-shelf components were used to collect data for this research:
1. Strap – worn across the individual's chest, with a compression strap indicating proper pressure of the puck inserted against the sternum.
2. Puck – sensor system, pressed against the sternum, held in place by the Bioharness strap, used to collect up to 36 hours of data
3. GPS device – *Global Positioning System* (*GPS*) worn on the shoulder of an individual and linked to the puck via blue-tooth technology
4. Loading dock – charges the pucks and allows download of data onto a computer.
5. OmniSense software – software consisting of two parts: OmniSense LIVE and OmniSense ANALYSIS, which are software tools which allow for either real-time viewing or post analysis of data.
6. GPS dock – charger for the GPS devices.

Metrics

The research team identified the following eight metrics for initial review, including: heart rate, breathing rate, core temperature, mechanical load, physiological load, minor impact, major impact, and posture. A brief description, adapted from (Zephyr Technology, 2012), of each metric is listed in Table 3 (Clevenger et al, 2018).

Table 3: Physiological Metrics

Metric	**Description**	**Measure (units)**	**Technical Notes**
Heart Rate	A measure of the number of heart beats per minute.	Heart beats per minute	Heart Rate is determined from analysis of 250Hz ECG data.
Breathing Rate	A measure of the number of breaths taken per minute.	Breaths per minute	Breathing is detected by a pressure sensor in the strap which detects torso expansion and contraction due to breathing.
Core Temperature	An estimate of the core temperature of an individual based on heart rate.	°C	Previous studies have validated the accuracy of this estimate and have also demonstrated that such a computational measurement can indicate physical stress before an individual reaches an unhealthy state (Buller & Hoyt, 2008).
Mechanical Load	Mechanical intensity over time, where mechanical intensity is a measure of instantaneous effort based on acceleration	Unitless	A measure of movement and acceleration.
Physio-logical Load	Physiological intensity over time, where physiological intensity is a measure of instantaneous effort based on heart-rate	Unitless	A measure of cardiovascular output.
Minor Impact	Measure of peak accelerometer magnitude change	Count	The range for minor impacts is 3g to 7g.
Major Impact	Measure of peak accelerometer magnitude change	Count	The range for major impacts is anything greater than 7g.
Posture	Measure of vertical position of a body relative to gravity.	Degrees from vertical	During a completely straight standing position, the posture will read as 0. Any lean forward will be positive and any lean back will be negative, up to 180 degrees in both directions.

Omnisense software was also used to calculate a metric called Heart Rate Confidence (HRC). HRC (%) is calculated based on an algorithm that uses electrocardiogram (ECG) (heartrate display) amplitude, ECG noise, and worn detection. During data processing, this HRC of 80% or greater was used as a threshold to verify data quality, based on a recommendation of Zephyr's representative.

Data Analysis

The Bioharness system stores data on pucks, which can be viewed either in real-time using a blue-tooth connection to OmniSense Live software, or after download using OmniSense Analysis software. Each puck has sufficient memory to hold 36 hours of data. For this research, data at one second intervals were manually downloaded at the end of each day for each of the five volunteers. Post processing of data consisted of the following steps:

1. Filter - data with less than 80% HRC were omitted.
2. Collate - data were separated into activities based on Pre-task Planning Logs.
3. Analyze - mean and standard deviations calculations were performed for each metric per each construction activity.

Results

Descriptive statistics were used to explore the pilot data collected for the five construction worker volunteers. Mechanical and physiological loads are the focus of this research since they serve as leading indicators of several of the other metrics identified. Specifically, mechanical load is the summation of mechanical intensity over time. Mechanical intensity is assessed based on peak acceleration (gravity [g] value) in one second intervals. Physiological load is calculated in a similar way, the summation of physiological intensity over time. It is a measure of total cardiovascular output and gives a good indication of an individual's overall level of effort. Physiological intensity is based on the percentage of heart rate over the individual's stored HRmax.

The following results are intended to serve as a demonstration of the characterization and comparisons that are possible using off-the-shelf equipment and readily available metrics. In general, further and detailed analysis of this pilot data is warranted (and subject of additional publications). Nevertheless, several high level observations are possible from the data as analyzed. First, using individual data collected, it is possible to compare individuals' stresses. Figure 2 is comparison of Volunteers C, D, and E's mechanical and physiological loads over a three day period of synchronously (i.e. under similar site and weather conditions) setting wall forms for the building's foundation.

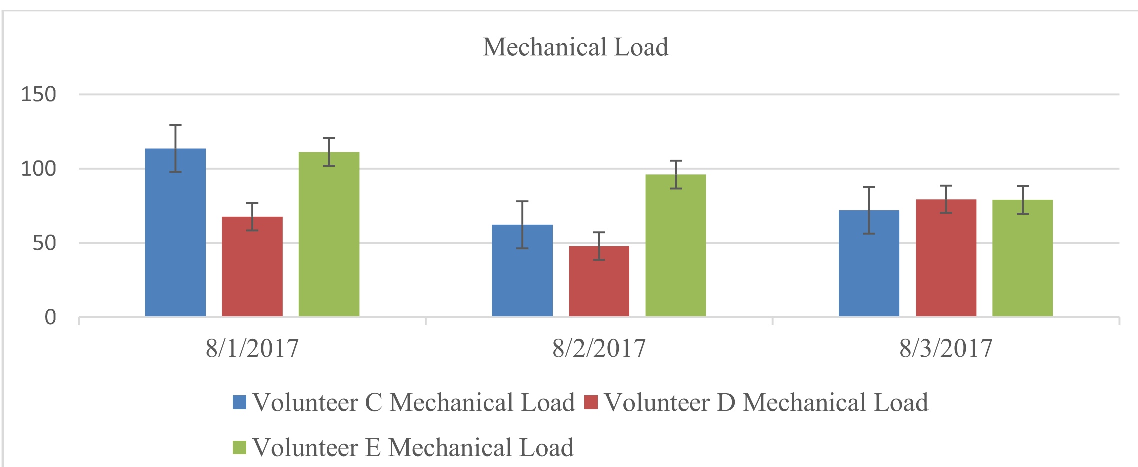

Figure 2: Average Mechanical Load per Day across Volunteers while Setting Wall Forms

Figure 2 and Figure 3 compare average mechanical and physiological loads of three construction workers over a three day period. Remembering that Volunteer C's BMI categorized him as overweight whereas Volunteer D's and E's were categorized as normal weight, one observation from the comparison, while anecdotal, is that a more overweight construction worker experiences significantly higher total physiological stress (related to cardiovascular output) during the course of the day than his or her peers. Differences in mechanical loads (related to peak acceleration) are less evident. Such a result is intuitive and suggests that a less fit worker has to use more effort to complete the same amount of work. Of note, the daily average temperature on August 3rd, the third day of data shown, was approximately 6°F cooler than the two previous data. While potential impact of temperature appears inconsistent across participants, there may be some indication that temperature has greatest impact on the cardiovascular output of the least fit individual.

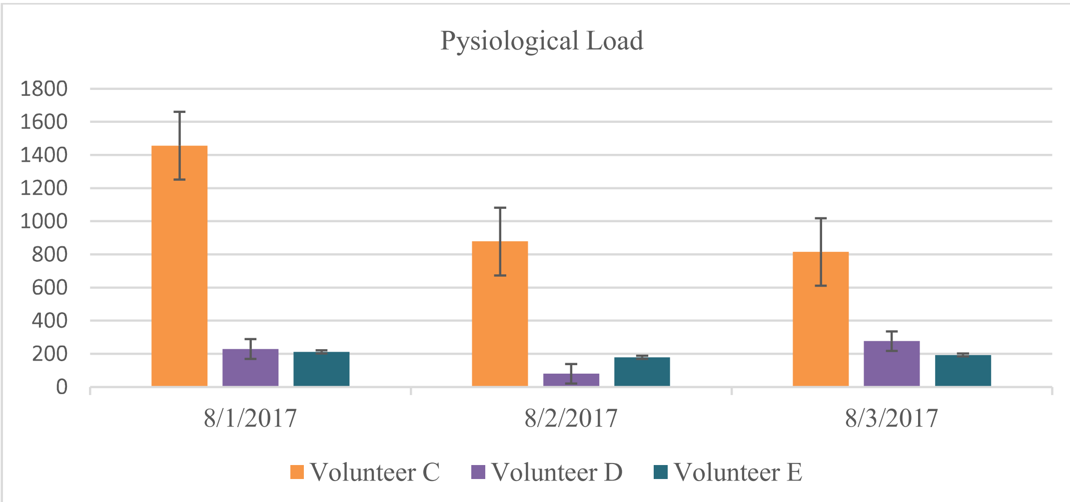

Figure 3: Average Physiological Load per Day across Volunteers while Setting Wall Forms

To further explore potential relationships between environmental conditions and mechanical and physiological loads as experienced by construction workers, the researchers analyzed these metrics for Volunteer A, alone over time. As shown in Table 3, Volunteer A operated the heavy equipment throughout all eight days of the study period. Note that Volunteer A's BMI categorized the individual as obese. Figure 4 shows mechanical and physiological loads along with average temperature and relative humidity.

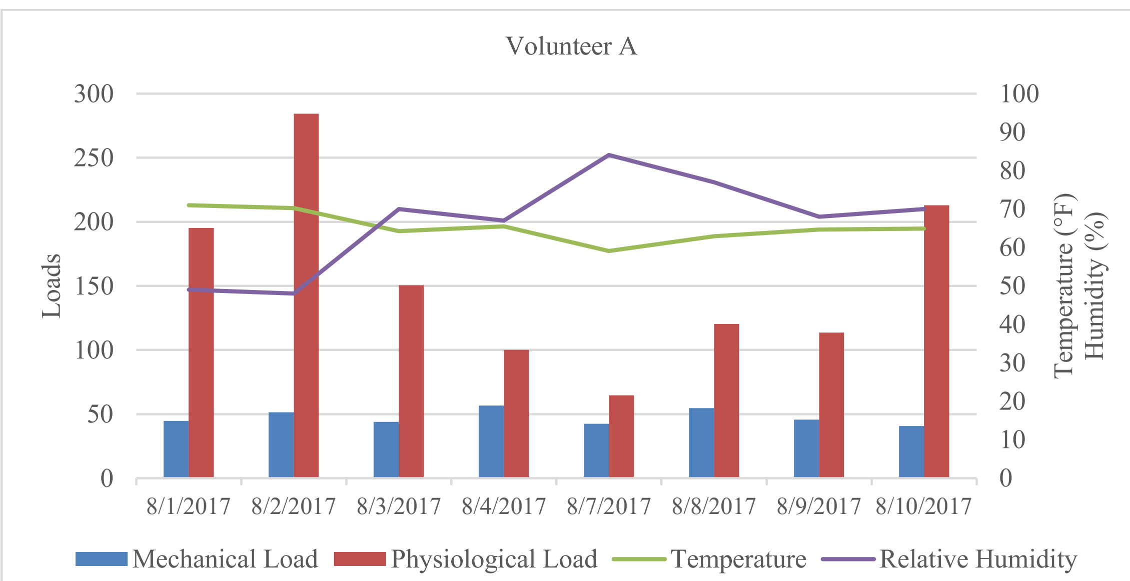

Figure 4: Average Mechanical and Physiological Loads for Volunteer A Operating Heavy Equipment along with Temperature and Humidity

Again, anecdotally, analysis of construction worker data suggests that there may be some level of correlation between the average ambient temperature and average relative humidity on-site and the cumulative physiological (cardiovascular) load experienced by an (obese) construction worker. However, weather data, was relatively similar on August 3rd and August 10th, yet the total physiological loads differed by over 40% for Volunteer A. No correlation is readily observable for mechanical load and temperature and humidity. Next the authors compared the calculated core body temperature relative to average ambient temperature. Figure 5 compares these values for the eight days studied. It is difficult to observe notable patterns based on the comparison shown in Figure 5.

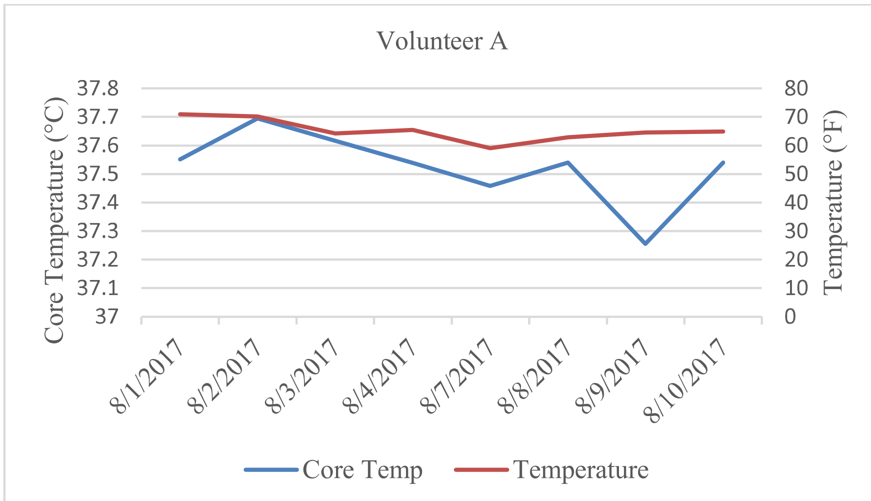

Figure 5: Estimated Core Temperature Operating Heavy Equipment compared to Daily Average Ambient Temperature

Finally, the authors used the data to explore potential differences in Mechanical and Physiological Loads experienced by workers when performing different construction activities. Figure 6 compares three workers performing two different tasks on two different days with relatively similar weather conditions on August 3rd and 4th.

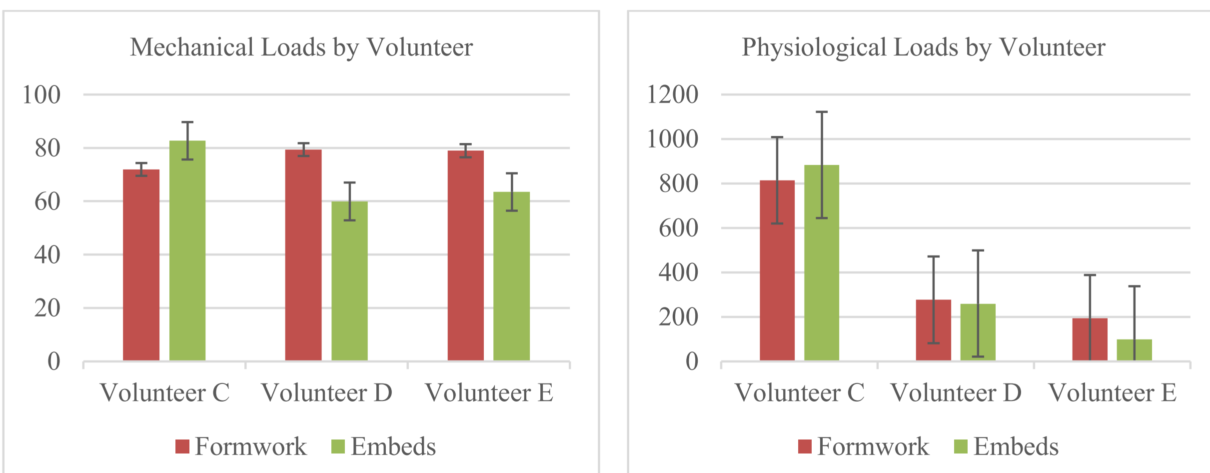

Figure 6: Comparison of Mechanical Loads (left) and Physiological Loads (right) across Volunteers performing two distinct construction activities

Initial observations based on Figure 6 suggest that for both (relatively fit) volunteer D and E work associated with preparing embeds for a foundation is less physically demanding than setting formwork. However, the same does not appear to be true for (less fit) Volunteer C.

Conclusions and Future Work

This research explores a set of pilot data collected over eight days by monitoring the physiological measures of five construction workers as they performed typical construction activities associated with constructing a foundation on-site in Colorado Springs, Colorado. While results are not generalizable due to small sample size, initial findings are promising and demonstrate how such data can be used to compare and analyze worker health and productivity across individual workers, environmental conditions and construction activities. While not included in the scope of this research, of particular interest for future research, is comparing professional construction workers' data to data for individuals at peak fitness performing similar construction activities. Initials comparison indicates average mechanical loads experienced by individuals at peak fitness are, on the order of, 20-80% less than those experienced by professional construction workers, and average physiological loads are approximately 60-65% less. The contribution of this research is to highlight research opportunities using physiological data and to motivate additional future research in this area.

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